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SPECTRUM OF COMET MOREHOUSE (1908 *c*)

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The exceptionally fine weather during the autumn of 1908, and the considerable northern declination of this comet have enabled us to study its spectrum under very favorable circumstances. Our researches were made exclusively on negatives obtained with objective-prisms. In 1903, one of us had already called attention to the advantages presented by the objective-prism in investigating the spectra of faint comets;[1] and, since then, we have applied this method to the study of the spectra of several comets.

INSTRUMENTS USED AND PHOTOGRAPHS TAKEN

In the present case we have employed three different instruments:

1. At the beginning, when the comet was comparatively faint, we were obliged to utilize an objective-prism of large light-power, but necessarily of low dispersion (2.2 mm between F and H). The prism had an angle of 20° 18′, and it was placed in front of a portrait lens 0.08 m in diameter, whose focal length was 0.30 m. This instrument was already used in photographing the spectrum of comet 1902 *b* and that of comet 1907 *d*.

2. The comet having considerably increased in brightness, we were enabled, during October and November, to substitute a prism

[1] *Comptes Rendus*, **136**, 743, 1903.

TABLE I

Date 1908—Paris M.T.		Exposure		Effective Length of Exposure	Comparison Star	Objective-Prism	Plate	Remarks on the Negatives
		Beginning	End					
October	3	$12^h 36^m$	$15^h 1^m$	$2^h 25^m$	*β Cephei*	No. 1	Panchr.	Bad comparison spectrum
	4	13 5	14 58	1 53	*γ Cassiopeiæ*	1	Panchr.	Fairly good
	4	15 49	16 47	0 58	*γ Cassiopeiæ*	1	Panchr.	Faint
	6	14 15	16 50	2 35	....	1	Pinac.	Intense, tail 6°
	11	7 7	7 37	0 30	....	1	L.V.	Fogged
	12	6 39	7 29	0 50	....	1	Pinac.	Good
	13	6 59	8 11	1 12	*Vega*	No. 2	Pinac.	Faint
	14	7 23	8 53	1 30	....	2	Pinac.	Fairly good
	15	8 41	9 31	0 50	....	2	Pinac.	Faint
	15	10 9	11 15	1 6	....	2	Pinac.	Faint
	16	6 40	10 30	3 40	....	2	Pinac.	Good
	17	10 0	12 2	2 2	*Vega*	2	Pinac.	Very satisfactory
	18	6 48	11 21	3 57	*Vega*	2	L.V.	Best spectrum for blue and violet
	19	6 27	12 23	5 56	....	2	L.V.	Very satisfactory
	20	9 25	10 25	1 0	....	2	Pinac.	Faint
	22	6 38	12 49	6 0	*Vega*	2	Pinac.	Very intense
	23	6 34	6 55	0 21	....	2	L.V.	Moderately good
	23	7 0	13 0	6 0	....	2	Pinac.	Very intense
	27	9 30	11 40	2 10	....	2	Pinac.	Moderately good
	28	7 46	11 15	3 29	....	2	L.V.	Very intense
	29	7 53	11 45	3 52	*Vega, Procyon*	No. 3	L.V.	Very faint; fogged
	30	6 20	11 20	5 0	*Capella*	3	L.V.	Good
	31	6 12	11 10	7 1	*Capella*	3	L.V.	Best spectrum for ultra-violet
November	1	6 27	8 30					
	6	6 4	8 4	2 0	....	3	L.V.	Good
	20	6 46	6 56	0 10	....	No. 2	L.V.	Good
	21	5 58	7 41	1 43	....	2	L.V.	Good
	27	5 42	7 25	3 7	*Capella*	2	Pinac.	Best spectrum from red to blue
	28	5 50	7 14					
	29	5 46	7 18	1 32	....	2	Pinac.	Faint; fogged

Abbreviations: Panchr. = Wratten Panchromatic plate; Pinac. = Wratten Pinacyanol plate; L.V. = Lumière "étiquette violette" plate; No. 1, with the prism of 20° 18′. No. 2, with the prism of 60°. No. 3, spar and quartz.

of 60° for the prism of 20° 18′, and thus to obtain higher dispersion (10.9 mm between F and H). 82 A/mm average

3. With the view of studying the ultra-violet, we also utilized a prismatic camera having a 60° prism of Iceland spar and a quartz object-glass 0.06 m in diameter with a focal length of 0.87 m (dispersion, 25.8 mm between F and H).

The spectroscopes were mounted on an equatorial telescope having an object-glass of 0.24 m aperture and 3.75 m focal length. This refractor, with a magnifying power of 140, was used as a guiding telescope. On 11 of the negatives we have printed the spectrum of a bright star, either on one side of the comet's spectrum or on both sides of it; and these comparison spectra enabled us to determine the wave-lengths of the comet's monochromatic radiations.

For the region extending from red to green, we used Wratten and Wainwright's "Pinacyanol" and "Panchromatic" plates; while for the blue and ultra-violet part we utilized Lumière's "étiquette violette" plates, particularly sensitive to the more refrangible rays of the spectrum.

We obtained in all 28 negatives, whose total exposure amounts to 72 hours 49 minutes. On p. 90 is an extract from our observational notebook.

MEASURING OF THE NEGATIVES AND DETERMINATION OF WAVE-LENGTHS

We have measured the negatives taken with the above instruments Nos. 2 and 3, the spectra obtained with instrument No. 1 not being sufficiently dispersive to give accurate results. A Zeiss comparator, with a microscope usually magnifying 4 diameters, was used in the measures. On each side of the monochromatic images of the comet were the wires of the micrometer. Two measures, one way and the other, were made; then the negative was reversed, and the same process repeated. Several plates were thus measured on various occasions separated by some weeks. The accuracy of the settings has never exceeded 10 μ, except for the doublet at λ 4256.9–4279.0, which was remarkably sharp and intense. The maximum discrepancies of all the measures of this doublet, on each of the 14 plates measured, do not exceed $\pm 4\ \mu$.

After trying different interpolation formulae, namely, Hartmann's, we finally adopted the following, which is quite sufficient in the present case:

$$\frac{1}{\lambda}=A+a\delta+b\delta^2+c\delta^3 ,$$

δ being the distances of the monochromatic images from an arbitrary point, λ the wave-length corresponding to the distance δ, and A, a, b, c, constant coefficients. A first series of coefficients was calculated in order to interpolate between λ 4340.7 and λ 6563.1; and a second series was similarly computed for interpolation between λ 3770.8 and λ 4861.5.

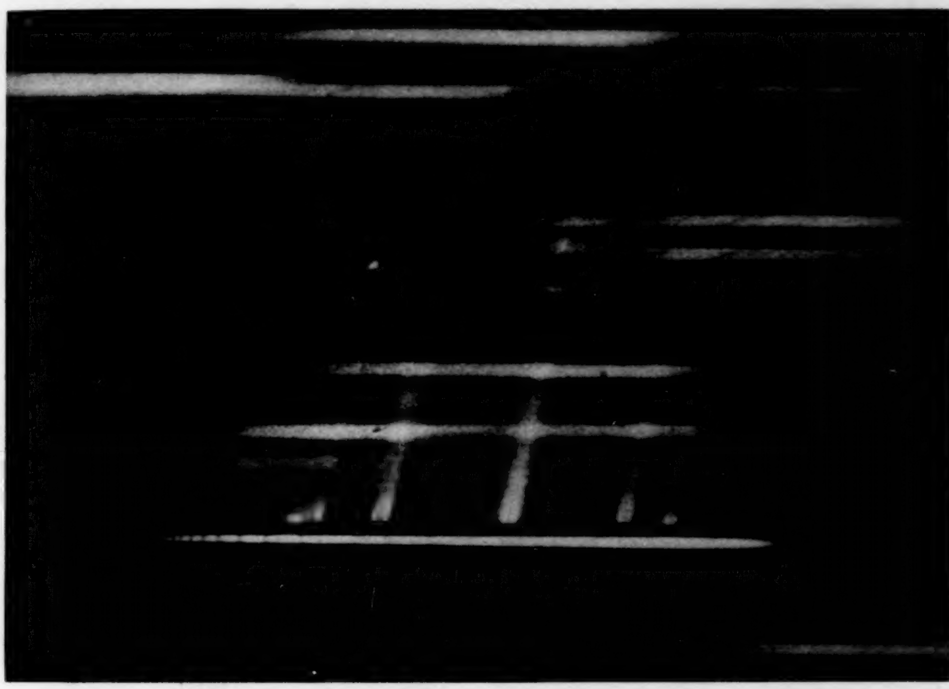
Toward λ 4000 the above maximum error of 10 μ in our settings entails an inaccuracy of 0.6 Å in the wave-length. As to the precision of the settings on the comparison spectra, we shall say that the positions of the hydrogen lines in the spectrum of *Vega* were found accurate to within 0.7 Å.

RESULTS

With the objective-prism of low dispersion we got an intense spectrum, showing seven distinct monochromatic images of the comet, though no continuous spectrum is visible. These images are located in the blue, violet, and ultra-violet. Hence comet Morehouse emitted only very refrangible rays, and was consequently blue. The spectrum extends to a considerable height, and the various images of the tail can be separated as far as 34′ from the nucleus. Beyond 34′, the monochromatic images of the tail are superposed, and the negatives show here nothing but a nebulosity which can be traced right up to the edge of the plate, that is to 6° from the head.

On the negatives taken with instruments Nos. 2 and 3, the monochromatic images of the comet are neatly doubled. This is clearly shown on Plate VI, which is an enlargement of a photograph taken with objective-prism 2 in the blue and violet. Four of these doublets are very strong and conspicuous, and in every interval between a pair and the one next there is a fainter doublet. Furthermore, in the yellow and ultra-violet, other feeble images are visible,

PLATE VI



THE SPECTRUM OF COMET MOREHOUSE

Photographed with 60° objective-prism on October 18, 1908, with exposure of $3^h\ 57^m$
Enlarged 4.7 times from the original negative

which turn out to be also double. A close examination of the negatives has enabled us to recognize the existence of 21 doublets. Of these, 18 have been doubled with a definiteness sufficient to enable us to measure the positions of both their components; as to the other 3 doublets, their faintness did not allow us to do more than determine their middle part.

Having remarked that between two strong doublets there generally was a weak one, we were led to suspect the existence of two series of doublets—a series of bright doublets and a series of faint ones; and we have inquired whether the lines of these two series were not distributed in the spectrum in accordance with some known law.

After trying a formula for a line spectrum (Rydberg) and a formula for a band spectrum (Deslandres), we found that the doublets were distributed according to the second law of Deslandres, which is that "the intervals expressed in frequencies $\frac{1}{\lambda}$ between the heads of bands of the same series increase in arithmetical progression." This law may be defined by the relation

$$\frac{1}{\lambda}=\frac{1}{\lambda_0}+an+bn^2,$$

n being an entire number.

If we consider each of the two lines composing the doublets as heads of flutings, the intense doublets give two series, A_1 and A_2, and the faint ones yield two other series, B_1 and B_2, that is to say, altogether four series.

We had computed the wave-lengths of the heads of these four series by applying the above formula containing three coefficients, λ_0, a, b, which can be calculated on the basis of the wave-lengths of three observed lines. But as we have a large number of lines whose wave-lengths we have measured, we have treated our results by the method of least squares in order to obtain the most probable values of the coefficients.[1] The observed and computed wave-lengths are given in Table II.

[1] We have been assisted in this part of our inquiry by M. A. Kannapell, who is familiar with such kind of work.

We thus see that there is a satisfactory agreement between the observed and computed wave-lengths. The small discrepancies may probably be attributed to the fact that the law of Deslandres is only approximate, as well as to the difficulty inherent in the measures themselves.

TABLE II

n	λ Computed	λ Observed	Difference O.−C.	λ Computed	λ Observed	Difference O.−C.
			Intense Series			
	Series A_2			Series A_1		
1	3291.5	3294.	+ 2.5	3270.5	3269.	− 1.5
2	3444.6	3446.	+ 1.4	3425.5	3436.	+10.5
3	3615.7	3611.	− 4.7	3597.6	3586.	−11.6
4	3808.2	3803.4	− 4.8	3790.0	3782.6	− 7.4
5	4026.1	4023.3	− 2.8	4006.4	4003.4	− 3.0
6	4274.6	4279.0	+ 4.4	4251.5	4256.9	+ 5.4
7	4560.8	4575.8	+15.0	4531.4	4549.2	+17.8
8	4893.8	4879.0	−14.8	4854.1	4846.1	− 8.0
9	5285.7	......	......	5230.1	......	......
10	5753.4	......	......	5673.8	......	......
11	6321.5	......	......	6205.0	......	......
12	7025.9	7027.4	+ 1.5	6852.6	6848.4	− 5.2
			Faint Series			
	Series B_2			Series B_1		
1	3372.3	3385.	+13.	3360.8	3357.	− 3.8
2	3528.2	3530.	+ 1.8	3517.0	3519.	+ 2.0
3	3705.2	3701.	− 4.2	3692.9	3687.	− 5.9
4	3907.2	3907.6	+ 0.4	3892.3	3898.2	+ 5.9
5	4139.8	4143.7	+ 3.9	4119.6	4114.0	− 5.6
6	4410.1	4411.9	+ 1.8	4381.5	4387.7	+ 6.2
7	4727.7	4721.9	− 5.8	4685.8	4695.3	+ 9.5
8	5105.4	5106.7	+ 1.3	5043.9	5021.1	−22.8
9	5562.0	5562.7	+ 0.7	5470.8	5482.2	+11.4
10	6124.1	......	......	5988.0	......	......

As to the three doublets, Nos. 9 and 11 of the strong series, and No. 10 of the faint series, they could not be neatly separated on account of their diffuseness, so that we have contented ourselves, as above stated, with taking their centers. Now, the position of these diffuse centers agrees with that of the middle of the computed doublets, as shown by Table III.

Calculation indicates that the doublet No. 10 of the strong series ought to be discernible at λ 5673.8–5753.4; but it was impossible to detect the slightest trace of it, probably because the

pinacyanol plate used presents in this region of the spectrum a marked minimum of sensitiveness.

TABLE III

Series	λ Computed	Computed Middle	Observed Middle	Difference O.−C.
A_1........... A_2...........	5285.7 5230.1	5257.9	5259.8	+ 1.9
A_1........... A_2...........	6321.5 6205.0	6258.8	6254.5	− 4.3
B_1........... B_2...........	6124.1 5988.0	6056.9	6020	−37. †

† Very difficult measure.

The data of the above table have enabled us to draw the diagram on p. 96. In the upper figure we indicate the frequency of the radiations; in the lower one, their wave-length. This second illustration is in a way a schematic reproduction of one of our negatives. (The enlargement is 2.6.)

As a test of possible theories, we have examined whether the interval between the components of the doublets had not varied with time. On this point we have confined our measures to the sharpest doublets at λ 4256.9–4279.0, with the result that, on 14 spectra, taken between October 15 and November 29, the distance in question had not changed, so far as can be determined by the limits of accuracy of our measures, which, as already mentioned, attain here ±4 μ or ±0.3 Å.

Now, in addition to the doublets, we found on our negatives that the more conspicuous pairs are attended, on the violet side, by a third, complete monochromatic image of the comet, whose wave-lengths are the following:

TABLE IV

Doublet	λ	Doublet	λ
No. 5, Series A ..	3990.6	No. 2, Series B	3508
No. 6, Series A...	4236.3	No. 6, Series B	4373
No. 7, Series A...	4522.7	No. 8, Series B	4986.7

The number of these images being insufficient, we cannot know whether their intervals also obey Deslandres' law.

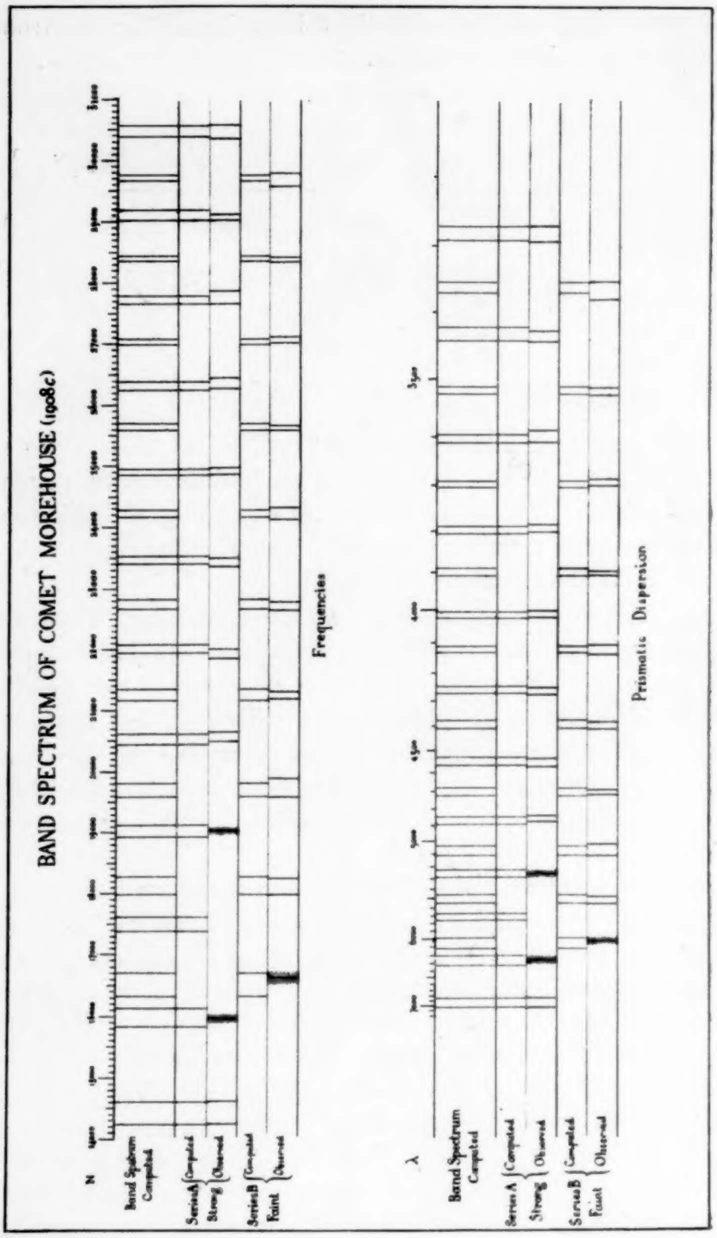
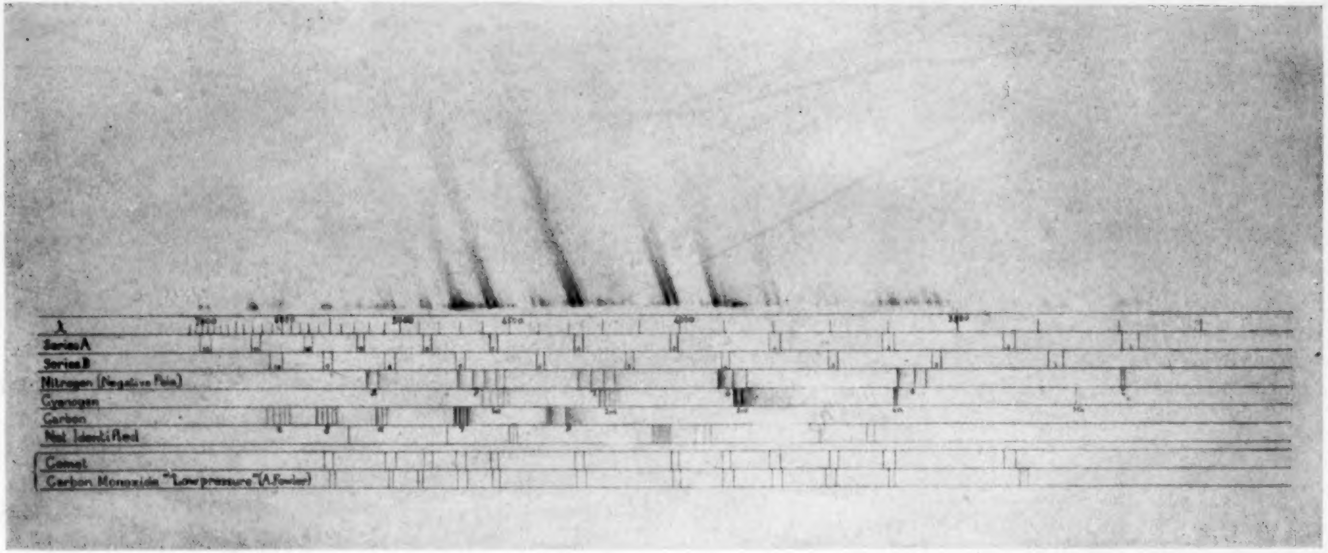

BAND SPECTRUM OF COMET MOREHOUSE (1908c)
N
Band Spectrum Computed
Series A Strong Computed Observed
Series B Faint Computed Observed
Frequencies
λ
Band Spectrum Computed
Series A Strong Computed Observed
Series B Faint Computed Observed
Prismatic Dispersion

PLATE VII



DRAWING FROM PHOTOGRAPH OF SPECTRUM OF COMET MOREHOUSE AND COMPARISON WITH THE SPECTRA OF DIFFERENT GASES

The intense and faint doublets, as well as the images just mentioned, are not the only monochromatic radiations found in the spectrum of the comet. A study of all our plates has enabled us to fix the position of a large number of condensations, of which some are found in the head only, the others being in the spectrum of both the head and the tail. We have drawn as faithfully as possible all the details visible in our spectra, and we give the resulting drawing in Plate VII. After obtaining a complete representation of the spectrum and of the wave-lengths of every radiation, we tried to identify the monochromatic images of the comet with the known spectra of various gases; and this comparison is given in the diagram of Plate VII, under the drawing, with which it coincides in wave-length.

PRESENCE OF THE SPECTRUM OF CARBON MONOXIDE

After having shown that the spectrum of comet Morehouse was essentially composed of bands, analogous to those yielded by a large number of gases, we have tried to identify it with some known spectrum. When we published a preliminary account of our inquiry,[1] we found no agreement between our spectrum of the comet and any published spectra, although the comet's radiations offered some analogy to those of various carbon compounds. But in 1909 Professor Fowler announced[2] that he obtained in his laboratory a spectrum which appeared almost identical with that of comet Morehouse; and he showed later that this new spectrum was that of carbon monoxide at very low pressure.[3] As soon as we heard of these interesting results, we compared the table of wave-lengths which Fowler gave with those of our spectrum of comet Morehouse.

The comparison in Table V will show the agreement between Fowler's wave-lengths and ours.

The accordance is particularly satisfactory for the lines of the two intense series, A_1 and A_2, which are, of course, more sharply defined on these plates than the lines of the faint series.

[1] *Comptes Rendus*, **148**, 759, 1909.

[2] *Monthly Notices*, **70**, 176, 1909.

[3] *Ibid.*, **70**, 484, 1910.

Yet we shall observe that there are two doublets for which the coincidence is not close. In the first place, Fowler's doublet at λ 3415–3429 does not agree with our doublet at λ 3430–3446. We are inclined to account for this discrepancy by the faintness of our spectrum in this region. It is possible that the most refrangible component of the doublet is not visible on our plates, and, further, that we have taken for the less refrangible component a radiation not belonging to the doublet. Secondly, Fowler's doublet at λ 4887–4916 does not agree with our doublet at λ 4846.1–4879.0. In this case, it would be hard to admit an error on our side, the image of the doublet being very sharp; and it is noteworthy that Fowler himself gives this doublet as "a possible pair."

TABLE V

CO Low Pressure (Fowler)	Comet	Series	$\Delta\lambda$ Comet—*CO* (Fowler)	*CO* Low Pressure (Fowler)	Comet	Series	$\Delta\lambda$ Comet—*CO* (Fowler)
λ 3415.0	λ 3436	A_2	−21.0	λ 4253.2	λ 4256.9	A_2	− 3.7
3429.0	3446	A_1	−17.0	4276.0	4279.0	A_1	− 3.0
3587.0	3586	A_2	+ 1.0	4545.4	4549.2	A_2	− 3.8
3602.0	3611	A_1	− 9.0	4570.5	4575.8	A_1	− 5.3
3693.0	3687	B_2	+ 6.0	4688.5	4695.3	B_2	− 6.8
3707.5	3701	B_1	+ 6.5	4715.0	4721.9	B_1	− 6.9
3781.0	3782.6	A_2	− 1.6	4887†	4846.1	A_2	+40.9
3797.6	3803.4	A_1	− 5.8	4916†	4879.0	A_1	+37.0
3891*	3898.2	B_2	− 7.2	5049	5021.1	B_2	+27.9
3907*	3907.6	B_1	− 0.6	5078	5106.7	B_1	−28.0
4001.3	4003.4	A_2	− 2.1	5473	5482.2	B_2	− 9.2
4020.4	4023.3	A_1	− 2.9	5510	5562.7	B_1	−52.7

* Indicated by Fowler as a possible pair.
† Indicated by Fowler as a faint band.

The spectrum of carbon monoxide at low pressure of Fowler and our spectra of comet Morehouse present another peculiarity which constitutes a proof of their identity. We found that on the spectra obtained with the objective-prism combination No. 3 the images of the brighter doublets at λ 4003.4–4023.3 and at λ 4256.9–4279.0 were slightly shaded toward the red, and that this shading extended to nearly one-half the interval of the doublet's two components. Now the doublets of carbon monoxide at low pressure also show this feature.

The number of our doublets is 21, while Fowler's are only 12. Hence there remain 9 doublets which were not observed in the laboratory. Furthermore, of the 12 doublets, 2 do not agree very satisfactorily, as already explained. But the accordance of the two spectra in their brightest and most conspicuous parts is too close to admit of any doubt that the doublets in the spectrum of comet Morehouse are practically identical with those of carbon monoxide at very low pressure.[1]

PRESENCE OF THE SPECTRUM OF NITROGEN

There is at λ 3914.7 an intense and complete image of the comet, neatly shaded on the violet side. Now, as far as the limits of accuracy of our measures go, this radiation coincides with the head of the most characteristic band in the spectrum of the negative pole of nitrogen. The presence of nitrogen in the gases of the comet thus seems highly probable; and, in order to corroborate this view, it is necessary to examine whether the other bands of the spectrum of this gas are also found in the comet. The spectrum of nitrogen obtained in the laboratory, at the cathode, consists of six bands. Of these, four, β, γ, δ, ϵ, coincide with complete monochromatic images of the comet; and the absence of the band a is probably due to the faintness of this radiation in our spectrum of the comet, and also to its location in the green. As to the group ζ, it would be difficult to affirm that it is found on our plates, superposed, as it is, on the less refrangible component of the doublet No. 1 in the A series. At any rate, as this image is notably brighter than that of the other component (a peculiarity which is not observable in the other doublets), it is very probable that there is, in this part of the spectrum, a superposition of the doublet's component and of the band ζ of nitrogen. Therefore, we think it safe to state that the cathodic spectrum of nitrogen is entirely recognizable in the comet's spectrum; and we will add that the gas seems to be as abundant in the head as in the tail.

[1] It should be remembered that the distribution in pairs of the chief radiations emitted by a comet was first recognized by M. H. Chrétien in the spectrum of comet Daniel (1907 *d*) (*Comptes Rendus*, **145**, 549, 1907).

Subjoined is the comparison between the two spectra:

TABLE VI

Laboratory Spectrum		Comet's Spectrum		Remarks on the Identification
Group	λ of Band-Heads	λ of the Condensations in the Head	Images of the Tail	
ζ	3296.1	3294.	....	See the notes on this identification in the text
	3298.5	......	....	
ε	3548.2	3553.	From 3530	
	3563.5	3569.	....	
	3581.5	......	to 3586	Component λ 3586 of doublets No. 3, series A_2, is superposed
δ	3857.1	......	From 3856	The third group of *CN* and the doublet No. 4, series B, are superposed
	3883.9	......	....	
	3913.7	3914.7	to 3915	*The most characteristic image*
γ	4166.3	......	From 4144	The second group of *CN* is superposed
	4198.7	......	....	
	4236.3	......	....	
	4278.0	......	to 4279	Component λ 4279.0 of doublet No. 6, series A_1, is superposed
β	4515.3	......	From 4523	
	4553.8	......	....	The doublet No. 7, Series A, is superposed
	4599.4	4613.9	....	
	4651.2	......	....	The group γ of carbon and the doublet No. 7, series B, are superposed
	4708.6	......	to 4722	
α	5150.0	......	....	Not observed: minimum of sensitiveness of pinacyanol plate
	5227.5	......	....	

λ after Deslandres, for the groups δ, ε, ζ.
λ after Hasselberg, for the groups β, γ.
λ Ångström and Thalén, for the group α.

PRESENCE OF THE SPECTRUM OF CYANOGEN

At the beginning of the ultra-violet there are two contiguous dots of great brightness, surrounded by faint nebulosity. Notwithstanding their marked intensity, these dots are not attended by an image of the comet's tail; they coincide with the first two heads of the cyanogen band, and they occur in the spectra of all comets. The study of the plates further reveals the other cyanogen bands, but only in the spectrum of the head. The absence of the fifth band of cyanogen is explicable by the faintness of the region in which it is situated. We may note that the second band of cyanogen, which some authors could not detect, is plainly visible on our plates.

Also, the wave-lengths of the third group of lines are all greater in the cyanogen than in the comet's spectrum. Yet these lines are too bright in the comet to allow of an error capable of accounting for the discrepancy.

Our comparison between the comet's spectrum and that of cyanogen is given as follows:

TABLE VII

Laboratory Spectrum		Spectrum of Comet's Head	Remarks on the Identification
Group	λ of Band-Heads		
5th	3360.1	......	Not observed (see notes in the text)
4th	3584.1	From 3569	Well-marked condensation. The component λ 3586 of doublet No. 3, series A_1, and the group ε of Nitrogen are superposed
	3586.0	......	
	3590.5	to 3611	
3d	3855.1	3855.9	Dot well marked
	3861.9	......	Invisible
	3871.5	3870.4	Intense dot
	3883.6	3881.5	Intense dot
2d	4166.9	From 4164	Condensation shading toward the violet
	4167.8	......	
	4180.5	......	
	4181.0	......	
	4197.2	......	
	4216.1	to 4223	
1st	4505	From 4520	Diffused condensation
	4526	....	
	4548	....	
	4582	....	
	4607	to 4614	

λ after Deslandres, for the fifth group.

λ after Kayser and Runge, for the second, third, and fourth groups.

λ after Thalén, for the first group.

PRESENCE OF THE SPECTRUM OF CARBON

There is also in the spectrum of the comet's head only, a conspicuous condensation stretching between the lines of the doublet No. 7, series B, and even on either side of it. This extensive nebulosity is easily identified with the band in the Swan spectrum, while other groups of Swan's also occur in the comet.

We summarize here our observations of the coincidence of the Swan spectrum with that of the comet:

TABLE VIII

Laboratory Spectrum		Spectrum of Comet's Head	Remarks on the Identification
Group	λ of Band-Heads		
β	4311.0	4305	Image faint
	From 4365.0 to 4381.9	4372	Image faint
γ	From 4682.0 to 4736.0	From 4637 to 4746	Intense condensation, extending in the interval comprised between these wave-lengths
α	From 5097.5 to 5164.0	From 5107 to 5163	Diffused condensation, extending in the interval comprised between these wave-lengths
δ	From 5466.0 to 5633.0	....	Not observed; minimum of sensitiveness of pinacyanol plate
ε	From 5953.5 to 6187.3	 6024	Diffused condensation, whose middle only is here given

λ From Kayser and Runge, for the group from 4365.0 to 4381.9.

λ From Ångström and Thalén, for the groups β, γ, α, δ, ε.

RADIATIONS NOT IDENTIFIED

The condensations of which we have spoken do not constitute the whole of the comet's spectrum, for at least 12 other monochromatic images can be traced. All these are faint, though fairly well defined; and we were not able to determine their origin.

They may be described as follows:

TABLE IX

λ	Description
3629	Image of the head only
3641	Image of the head and tail
3721	Image of the head only
3932	Image of the head, with faint tail
3949.2	Image of the head, with faint tail
3969.1	Image of the head only
4023.4 / 4067.7	Condensation in the head and in the tail, extending in the interval comprised between these wave-lengths
4458.5	Image of the head only
4475.7	Image of the head only
4492.6	Image of the head only
4771.9	Image of the head and tail
5368.7	Image of the head only

ABSENCE OF A CONTINUOUS SPECTRUM

On none of our negatives could we find any trace of a continuous spectrum. It is true that on many plates there is a band extending over the images of the head, and having the appearance of a continuous spectrum. But a more careful examination of the negatives shows that in each case this band is nothing but the spectrum of a star, accidentally superposed on the spectrum of the head. The proof of this is that the band in question looks sharply delimited on both edges, and that its width is identical with that of the numerous stellar spectra which occur on the plate. Furthermore, the beginning of the band varies in position with the comet's spectrum on the various negatives, which shows plainly that it is in no wise related to the comet.

In certain cases, the superposition of a stellar spectrum on that of the comet's has helped us to detect certain faint condensations in the latter. It is a known fact that a feeble action of light produces a more visible effect on a slightly fogged plate than on one never having received any previous luminous action whatever.

The absence of a continuous spectrum is especially noticeable in the following four regions of our plates:

From λ	3800	3914	4415	4770
to λ	3840	4003	4470	4849

SPECTRUM OF SOME REMARKABLE PARTS OF THE TAIL

We know that the matter composing the tail of comet Morehouse was at one time the seat of violent movements. Frequently, luminous masses seemed ejected from the nucleus backward, and it was possible to follow their displacement in the tail. One of us has studied these movements and measured their speeds.[1] Now we deem it interesting to note that these luminous clouds, although coming from the head, did not show the spectrum of the head, when once in the tail; and thus it was that we could not detect in their spectrum the radiations either of cyanogen, or of carbon.

[1] *Comptes Rendus*, **147**, 1033, 1908.

POSSIBILITY OF CHANGE IN THE SPECTRUM

We have examined the whole series of our plates in order to see if any modifications occurred in the comet's spectrum. From October 14 to 28 no change could be noted. Later, however, on November 21, when we were able to obtain a new negative with spectroscope No. 2, we found that three images at λ 4458.5, 4475.7, 4492.6, which were previously blended in the same condensation, could now be neatly separated. But as this peculiarity is recorded on only one plate, we dare not assert that we have to deal here with a real change in the spectrum of the comet.

SUMMARY

The results of our investigations may be summed up as follows: the spectrum of comet Morehouse was composed: (*a*) of four band spectra, which we attribute: (1) to carbon monoxide; (2) to nitrogen; (3) to cyanogen; (4) to carbon; and (*b*) of some faint radiations which it was not possible to identify.

Cyanogen and carbon were present only in the head; while carbon monoxide and nitrogen were the elements constituting the whole comet. The spectrum of carbon monoxide at low pressure was the most conspicuous one; then came, in order of decreasing brightness, that of nitrogen, that of cyanogen, and, lastly, the spectrum of carbon.

In conclusion, we wish to express our indebtedness to M. C. Flammarion for having allowed us to mount our spectrographs on the equatorial of his Observatory at Juvisy, and to M. F. Quénisset for his kind collaboration in obtaining the plates.

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PARIS
February 1911

THE DISCOVERY OF ECLIPSING VARIABLE STARS

By JOEL STEBBINS

It has often been pointed out that all spectroscopic binary stars would be eclipsing variables for observers properly situated in space; also that in those spectroscopic binaries thus far discovered, the fainter components must be relatively of considerable size. It is known that those systems which appear as eclipsing variables from the earth are of low density as compared with our sun, but we should expect that the most tenuous systems would, as a class, furnish most of the eclipsing stars. Also, if in a certain number of short-period spectroscopic binaries, there is not a certain proportion of eclipsing stars, then it should be possible to assign a lower limit to the density of these objects as a class.

Let us first investigate the density of the stars of shortest period, assuming that we have to deal in each case with two separate bodies, approximately spherical in form, whose relative orbit is circular. The radius of the larger component may be taken as unity, irrespective of whether or not this body is the brighter or more massive of the pair. Further let

d_0 = the mean density of the system, referred to the sun,
κ = the radius of the smaller body,
a = the distance between centers,
R = the ratio of the astronomical unit to the sun's radius,
P = the period in days,
T = the earth's sidereal period of revolution.

Then we have the well-known equation

$$d_0 = \frac{a^3 T^2}{R^3 P^2 (1+\kappa^3)},$$

and introducing the numerical values, $T = 365.256$ days, and $1/R = \sin 15' 59''.63$,

$$d_0 = [8.1282] \frac{a^3}{P^2(1+\kappa^3)}, \tag{1}$$

the constant being a logarithm. Equation (1) gives at once the mean density of a system when P, κ, and a are known, but it also determines the lower limit of density for any binary star of known period. Since by hypothesis we are concerned with two bodies, we have $a^3 > 1+\kappa^3$ and therefore

$$d_0 > \frac{[8.1282]}{P^2}.$$

Putting $d_0 = 1$ we then find $P > 0.116$ days; or a binary system with a period of 0.116 days must be more dense than the sun. Since the density of air on the solar standard is 0.00093, it similarly follows that a binary which revolves in 3.80 days is more dense than air. These limits are on the assumption that the system is composed of an indefinitely small satellite revolving close to the primary, but if we assume $\kappa = 1$, the limiting periods are doubled, and become 0.232 and 7.60 days for the solar and atmospheric densities respectively. It is thus evident that though short-period stars may be quite rare, there is a lower limit to the density which is by no means comparable with the nebular condition.

In the cases just considered, the two components are close together, but if we increase a the computed density is much greater. Remembering that κ is always the radius of the smaller body, we have $1+\kappa^3 < 2$, and in place of equation (1) we may write the inequality

$$\frac{a^3}{d_0} < \frac{2P^2}{[8.1282]}. \qquad (2)$$

We now put $d_0 = 1$, and compute a for different values of P, which give

TABLE I

$P = 0^d25$	0^d5	1^d0	2^d0	5^d0	10^d0
$a < 2.10$	3.34	5.30	8.41	15.5	24.6

That is, a binary star with period of 0.25 day either has a mean density greater than that of the sun, or else the distance between centers is less than 2.10 times the radius of the larger body. The period of 0.25 day is not exorbitantly small, for in Campbell's

"Second Catalogue of Spectroscopic Binary Stars"[1] there are four stars with periods known to be less than one day, the shortest being that of *β Cephei*, which Frost found to be 0.1904 day. Also in Hartwig's latest list of variables[2] there are 14 stars of the *Algol* type with periods shorter than a day. There are in addition more than 30 stars of short period, and of the *Antalgol* type, with equally rapid changes, but while most of these sytems are no doubt spectroscopic binaries, it is not certain that the components are entirely separated.

At present it is conventional to include in the class of *Algol* variables all stars which are normally of constant brightness, but which suffer a diminution of light at regular intervals. Stars of the *β Lyrae* type have two unequal minima, and continuous variation in brightness. It is probable that future observations will demonstrate that very few of the *Algol* stars are perfectly constant at maximum light, and we should expect a series intermediate in type between a star with no secondary minimum, and one with two equal minima. In view of the results from radial velocity determinations, the general term *eclipsing variables* seems appropriate for all stars listed at present under the *Algol* or *β Lyrae* types.

The alternative that rapidly moving spectroscopic binaries must be either dense or close together, brings us to the question of the probability of eclipses of these stars as seen from the earth. Of course the magnitude of the eclipse depends upon the relative size of the fainter body. Whatever may be our preconceived notions on the subject, the fact is that, in those eclipsing systems where the relative dimensions have been inferred from a thoroughly determined light-curve, the "companion" has in most cases been found to be the larger. For the present purpose we shall not be far in error if we assume that in the short-period systems the components are of the same size. Stroobant[3] has pointed out that if the normal *Algol* system be considered as composed of a bright and a dark body with equal radii, and of relative

[1] *Lick Observatory Bulletin*, **6**, 17, 1910.

[2] *Vierteljahrsschrift der astronomischen Gesellschaft*, **45**, 341, 1910.

[3] *Bulletin de l'Académie royal de Belgique*, 1909, 329.

separation, $a=8$, then the probability is $1/7.7$ that the orbit of such a system, situated at random, would be inclined so as to give us an eclipse of 0.5 stellar magnitude, or more. In other words, for every *Algol* star that is discovered there must be about 7 other such systems whose orbit planes do not pass near the sun. The arbitrary limit of 0.5 magnitude was adopted by Stroobant because practically all of the known eclipsing stars have a range greater than this amount. While this limit is all right for the random discovery of *Algol* stars, an experienced visual observer can detect a much smaller change in the light of a star whose period is known, and it seems that a systematic study of spectroscopic binaries would undoubtedly result in the discovery of more eclipsing variables. With the selenium photometer attached to our 12-inch telescope the measures are ordinarily limited to stars brighter than the third magnitude, but for stars as bright as magnitude 2.0 it is no exaggeration to state that a variation of 0.10 magnitude may be called conspicuous. Recently we made an observation which was discordant by 0.07 magnitude from previous results for the same star, and as will be shown later this enabled us to prove that the star is a variable. For the purpose then we may adopt the limiting amount of eclipse to be such that a star with a dark companion will vary by 0.10 magnitude, and if the components are of equal brightness, the same inclination of orbit will produce a range of about 0.05 magnitude, which is still within the power of the instrument.

In a random distribution of the orbit planes we have to determine the probability that the inclination will lie between 90° and i, where i is the limiting angle for an eclipse of assigned amount. The area of the zone of the hemisphere, within which one of the poles of the orbit must lie, is equal to $\cos i$ times the total area of the hemisphere. Hence if we compute the value of i necessary for an eclipse of assigned magnitude, the probability that such an eclipse or one greater will occur is given by $\cos i$. Consider the projected disks of the two bodies, and let

M_0 = the obscured area of the bright disk at minimum,
J_0 = the ratio of the light at minimum to that at maximum,
$2\eta_0$ = the angle at the center of the bright disk subtended by the common chord.

For $\kappa=1$ the following equations are readily established:

$$2\eta_0-\sin 2\eta_0=M_0=\pi(1-J_0)\ ,$$

$$\cos i=\frac{2\cos\eta_0}{a}\ .$$

On the assumption of one perfectly dark component and a loss of 0.10 magnitude, we have $J_0=0.912$, and with $a=5$ there follows $i=70\overset{\circ}{.}8$, cos $i=0.33$. Therefore, of those binaries with equal radii and $a=5$, one third are eclipsing systems whose minima may be detected. For $a=10$ we find cos $i=0.16$, and the proportion of variables is one-sixth. If we compare these results with Table I, it is evident that there must be eclipsing stars among the binaries of short period, unless the systems are quite dense, or the companions very small. We now put these results in the form of three alternative statements, some one of which must be true.

1. Among the spectroscopic binaries of very short period there are a considerable number of eclipsing variables, which have a range of 0.05 magnitude or more.

2. These systems as a class are more dense than the sun.

3. The fainter components are much smaller than the bright components.

Let us now go back and note upon what tacit assumptions these alternatives are based. Equation (1) holds in general only for spherical bodies with a symmetrical distribution of density, but if two bodies are near enough to be distorted from the spherical form, the value of a would be so small as to produce a high probability of eclipses. In the more exaggerated cases of two stars in contact or partially coalesced, the systems which vary in light must be the rule rather than the exception. It is well known that all of the *Algol* stars whose spectra have been determined are of "early" type, B, A, and a few of class F, according to the Harvard classification. Likewise it is known that the spectroscopic binaries of shortest period are of the same spectral types. If the density of the *Algol* stars is typical of others of the same spectrum, we cannot admit a high density for the rapid spectroscopic binaries. To the other alternative, that the fainter bodies are much smaller than the primaries, we have the objection already mentioned, that

where the relative size can be determined the companion is usually the larger body. Also where the spectra of both components are visible, we apparently have stars of nearly the same size, though it seems to be the rule that the fainter body is the less massive. However, in systems which show only one spectrum and which have large values of $a \sin i$, there cannot be a large disparity in the masses without giving the primary an enormous mass as compared with the sun. In the case of *δ Orionis*, where $P=5.73$ days, and $a \sin i=7{,}900{,}000$ km, if we assign as low a relative mass as $1/4$ to the secondary, there results for the bright body, $m \sin^3 i=60\odot$.

The discovery of eclipsing systems among spectroscopic binaries is a perfectly definite problem of observation. For any star the time of principal minimum is easily predicted from the spectroscopic elements, being the instant when $u=90°$, and if two spectra are visible there will ordinarily be a second minimum at $u=270°$. It is natural to look for such variables among the orbits which have a large $a \sin i$; in fact, the size of this element is perhaps an additional measure of the probability of an eclipse.

Another consideration is that there is a strong tendency for stars of the *Algol* type to occur near the galaxy. This is true of the 88 stars in Hartwig's list for 1911, almost none of which are far from the Milky Way. I learn from Professor Pickering that a study of the distribution of all known variables is being completed at Harvard, and no doubt this peculiarity of the location of eclipsing variables will be fully discussed. Since there is known to be a preponderance of first-type stars in the Milky Way, and the few *Algol* variables of known spectra are in the same class, the general spectral type of the *Algol* stars is doubtless indicated by their preference for the galaxy.

Whatever weight the foregoing conclusions have in the judgment of others, to myself they seem well founded, for the good reason that the first *two* stars for which I was able to make a thorough test have turned out to be eclipsing variables. In fact, it was this surprising circumstance which led me to consider the probability of eclipses being visible from the earth. The first star, to which reference has already been made, is *β Aurigae*,

the results for which are in the following article; the second is the well-known suspected variable *δ Orionis*. The study of the latter is not completed, but it may be stated that there are two unequal minima observed close to the times predicted from Hartmann's spectroscopic elements. The extreme range of *δ Orionis* is not far from 0.10 magnitude, and as I intend to continue observing this star until a thorough light-curve is obtained, this statement as to its variation is sufficient for the present. Of course we have other stars on our observing program, but during the past season we have been more concerned with the determination of good light-curves than with the wholesale search for new variables. It may be worth while to call attention to a favorable case among the bright stars, namely, *α Virginis*. This star is *H. R.* 5056, magnitude 1.21, spectral type B2, period 4.01 days, two spectra visible, and (a_1+a_2) sin i=18,000,000 km. Unfortunately there are two obstacles in the way of an exhaustive study of *α Virginis*, the lack of a suitable comparison star, and the close approach of the period to 4 days. At the present writing the hypothetical eclipses occur in the day time, and it will be several months before they take place while the star is near the meridian during the night.

It is always dangerous to predict the nature of future discoveries, but from the preceding considerations it is evident that the spectroscopic binaries furnish the means of a new departure in photometric observation. At present the discoverers of variable stars examine presumably hundreds of objects for each new variable that is found. It appears that a systematic study of the spectroscopic binaries at the favorable epochs would result in the discovery of at least a few eclipsing systems, though it is not probable that the writer or anyone else will repeat the experience of finding two new variables in the first two stars observed.

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April 21, 1911

A NEW BRIGHT VARIABLE STAR, *β Aurigae*

By JOEL STEBBINS

In the spring of 1910, when the study of the light-curve of *Algol* with the selenium photometer was nearing completion, I made a list of bright stars which are known to be short period spectroscopic binaries, and among those which seemed to promise a possible variation in light was *β Aurigae*, *H.R.* 2088, magnitude 2.07. This star was then too low in the west for satisfactory measures, and it was necessary to wait six months, until September 20, 1910, when observations were begun and continued every clear night for a month without finding any change of significance. On October 23 I was surprised by a good observation which placed the star 0.07 magnitude fainter than it had been on previous nights. The spectroscopic period being 3.96 days, if this were an eclipse it would be repeated two nights later, since the spectrum plates reveal two components of about equal intensity. This discovery was followed up, and the eclipses were observed at every opportunity. I had intended to measure the star's light throughout the entire period of the orbital variation, and it happened that the times of eclipse were not computed until after the discovery with the photometer. When the computation was made, and it was seen that the minima were occurring close to the predicted times, it was determined to do everything possible to secure the best light-curve. Here at last is the ideal case for which astronomers have been looking, an eclipsing variable star with the spectra of both components visible, and for which there are reliable determinations of parallax. A good light-curve would give us not only the absolute diameters of the components, but also the surface intensity of each. The spectrum of *β Aurigae* is Class A p, and up to the present it has not been directly determined whether the first-type stars have surfaces which per unit area are more or less luminous than the sun.

The method of observation with the selenium photometer has been described in a former paper,[1] and since that work only a few

[1] *Astrophysical Journal*, **32**, 185, 1910.

minor improvements have been made, which, however, have increased the accuracy of the results. In the first arrangement, the extra-focal star image, 7 mm in diameter, was made to fall upon a selenium surface of 26×18 mm, and the guiding was by means of the regular finder of the 12-inch refractor. The holder of the selenium cell has since been made anew, and the guiding is now accomplished by means of a small total reflecting prism, which is inserted in the center of the converging beam, about 16 cm in front of the focus. This prism intercepts not more than 2 per cent of the light, and an eyepiece and crosswires placed in the direction of the reflected rays furnish a satisfactory means of keeping the main star image at the same position on the selenium. With the better guiding system it was safe to diaphragm the effective selenium surface to a diameter of 10 mm, which reduces the effect of the sky near full moon. The arrangement of the ice-pack about the selenium has also been modified, with the result that the temperature control is improved, especially in warm weather.

Another change from previous practice was to alternate more rapidly from star to star. On *Algol* the normal plan was to make exposures upon the comparison star and variable to the number of 4, 8, and 4, while for β *Aurigae* this was changed to 2, 6, and 2 exposures. The brighter the star the fewer the readings that are required to measure its light with the same probable error, but it was with considerable hesitation that I decided upon a schedule requiring more time upon one star than the other. In the long run, if the same time is allotted to each star, there is an equal probability of passing cloud or haze affecting the measures of each object, but if more time is consumed in observing the variable, there is a possibility of a preponderance of errors in one direction. In the present work, a set of measures, 4 exposures on the comparison star and 6 on the variable, required a minimum of 12 minutes, or we observed at the rate of 5 sets per hour. As compared with visual observations this is something of a snail's pace; but as I have noted before, if we could admit occasional errors of one- or two-tenths of a magnitude, bright stars could be measured with the selenium photometer at the rate of one star per minute, or as fast as a telescope can be manipulated.

The adopted comparison star for *β Aurigae* is *β Tauri*, which is 17° distant, but this disadvantage is in part offset by the high altitude at which these stars culminate, within 5° and 12° of the zenith. The correction for absorption was based upon Mueller's Potsdam table,[1] which for zenith distances up to 70° may be represented within 0.01 magnitude by the formula

$$\text{Reduction to zenith}=0.23 \text{ mag. } (\sec z-1).$$

The zenith distance of each star was computed for each half hour of sidereal time, and the absorption correction is given in Table I.

TABLE I

Sidereal Time	Differential Absorption	Sidereal Time	Differential Absorption
	mag.		mag.
1^h0	+0.013	5^h0	0.000
1.5	+0.006	5.5	+0.001
2.0	0.000	6.0	+0.004
2.5	−0.002	6.5	+0.006
3.0	−0.003	7.0	+0.011
3.5	−0.003	7.5	+0.018
4.0	−0.002	8.0	+0.027
4.5	0.000	8.5	+0.037

It is evident that under favorable conditions these two stars may be compared continuously for more than six hours, with no correction for absorption as great as 0.020 magnitude. However, it is my experience that the average night at this station has a coefficient of absorption somewhat greater than 0.23 magnitude, and the tabular correction has been multiplied by a factor varying from 1.0 to 2.0, which was derived from additional observations of *β Orionis*, taken for the purpose on all nights when the differential absorption was more than 0.003 or 0.004 magnitude. In all cases the observations were discontinued at sidereal time 8.0 hours. Whatever method is used to eliminate or correct for the absorption, there is always the danger from sudden changes in transparency of the air, and in spite of our utmost care I believe that a considerable portion of the outstanding errors in the results for *β Aurigae* are due to atmospheric causes. One of the defects of the selenium photometer

[1] *Die Photometrie der Gestirne*, Leipzig, 1897, p. 515.

TABLE II

OBSERVATIONS OF *β Aurigae* NEAR MINIMA

Date	G.M.T.	Phase	Difference of Magnitude	Absorption	Remarks
1910			mag.	mag.	
October 1........	$20^h 42^m$	$-5^h.85$	0.366	−0.003	
	21 14	− 5.32	.356	− .002	3 sets
October 7........	21 00	43.43	.361	− .001	
	21 33	43.98	.347	.000	3 sets
October 9........	20 31	− 4.10	.320	− .002	
	21 02	− 3.58	.315	− .001	3 sets
October 23........	20 36	46.90	.426	.000	
	21 07	47.42	.423	.000	3 sets
October 25........	20 56	0.18	.406	.000	
	21 22	0.62	.392	+ .002	
	21 52	1.12	.405	+ .005	
	22 22	1.62	.386	+ .008	
	22 48	2.05	.402	+ .014	
	23 13	2.47	.369	+ .019	
October 27........	17 20	44.58	.338	+ .002	
	17 52	45.12	.331	− .002	
	18 18	45.55	.390	− .002	
	18 43	45.97	.419	− .003	
	19 08	46.38	.405	− .002	
	19 33	46.80	.458	− .001	
	19 58	47.22	.434	.000	
	20 24	47.65	.472	.000	
	20 55	48.17	.415	+ .001	3 sets
November 2......	16 14	− 2.58	.348	+ .023	
	16 38	− 2.18	.364	+ .011	
	17 03	− 1.77	.374	+ .002	
	17 29	− 1.33	.430	− .003	
	17 55	− 0.90	.444	− .005	
	18 20	− 0.48	.459	− .006	
	18 46	− 0.05	.413	− .005	
	19 26	0.62	.425	− .002	
	20 07	1.30	.411	.000	
	20 32	1.72	.380	+ .002	
	20 58	2.15	.398	+ .005	
	21 25	2.60	.354	+ .007	
	21 54	3.08	.382	+ .011	
	22 24	3.58	.358	+ .016	
	22 50	4.02	.336	+ .024	
November 8......	17 51	48.02	.435	− .006	3 sets
November 10......	16 14	− 0.65	.406	+ .006	
	16 40	− 0.22	.450	.000	
	17 06	0.22	.476	− .003	
	17 36	0.72	.429	− .004	
	18 03	1.17	.412	− .004	
	18 28	1.58	.390	− .004	
	18 54	2.02	.374	− .001	
	19 20	2.45	.364	.000	
	19 45	2.87	.366	.000	
	20 12	3.32	.348	+ .002	
	20 41	3.80	.360	+ .006	
	21 10	4.28	.360	+ .010	

TABLE II—*Continued*

Date	G.M.T.	Phase	Difference of Magnitude	Absorption	Remarks
1910			mag.	mag.	
November 10......	$21^h 37^m$	$4^h.73$	0.378	+ .016	
	22 10	5.28	.363	+ .027	3 sets
November 24......	15 41	49.70	.386	.000	
	16 06	50.12	.366	− .001	
	16 31	50.53	.366	− .002	
	16 56	50.95	.367	− .003	
	17 22	51.38	.351	− .002	
	17 47	51.80	.380	− .001	
	18 12	52.22	.356	.000	
	18 38	52.65	.353	.000	
	19 04	53.08	.360	.000	
1911					
February 9........	13 47	− 5.07	.378	.000	
	14 12	− 4.65	.358	+ .002	
	14 38	− 4.22	.378	+ .004	
	15 03	− 3.80	.348	+ .006	
	15 28	− 3.38	.330	+ .012	
	15 53	− 2.97	.396	+ .017	
	16 18	− 2.55	.386	+ .026	
February 15.......	12 36	42.68	.376	− .001	
	13 02	43.12	.379	.000	
	13 26	43.52	.432	+ .001	
	13 51	43.93	.318	+ .004	
	14 16	44.35	.319	+ .009	
	14 41	44.77	.398	+ .012	
February 21......	13 08	− 2.88	.388	.000	3 sets
February 23......	12 42	44.68	.341	.000	
	13 06	45.08	.370	+ .001	
	13 31	45.50	.354	+ .003	
	13 58	45.95	.352	+ .005	
	14 22	46.35	.476	+ .008	
	14 48	46.78	.418	+ .012	
	15 14	47.22	.442	+ .019	
	15 38	47.62	.434	+ .026	
March 13.........	12 55	1.67	.382	+ .008	
	13 20	2.08	.371	+ .012	
	13 45	2.50	.366	+ .020	
	14 16	3.02	.373	+ .032	
March 19..........	13 13	50.90	.330	+ .012	
	13 38	51.32	.341	+ .018	
	14 02	51.72	.342	+ .026	
March 23.........	13 18	51.95	.344	+ .025	
	13 44	52.38	.372	+ .035	
Observations between Minima					
1910					
September 20.....	21 02	15.58	.361	− .005	
27.....	20 49	88.35	.343	− .003	
28.....	20 50	17.33	.343	− .005	
29.....	20 55	41.42	.350	− .005	
October 6.....	20 52	19.28	.360	− .002	
16.....	20 57	69.32	.344	.000	

TABLE II—*Continued*

Date		G.M.T.	Phase	Difference of Magnitude	Absorption	Remarks
1910				mag.	mag.	
October	18	21^h01^m	22^h33	0.344	0.000	
	28	20 23	71.65	.348	.000	
	30	20 11	24.42	.343	.000	
November	21	19 33	76.60	.346	+ .004	
	25	20 38	78.65	.346	+ .021	
	29	16 29	75.45	.334	− .004	
	29	17 32	76.50	.365	− .001	
December	7	15 57	76.83	.365	− .004	
	13	14 47	29.58	.329	− .001	
	20	14 57	7.68	.363	− .003	
	20	16 01	8.75	.382	− .002	
	24	16 25	10.12	.342	.000	3 sets
	26	13 54	55.60	.350	− .001	
	26	14 58	56.67	.366	− .003	
	26	16 01	57.72	.351	− .001	
1911						
January	3	15.52	59.47	.363	.000	
	3	16 54	60.50	.356	+ .004	
	4	18 03	85.65	.353	+ .013	
	8	14 10	82.72	.352	− .003	
	8	15 17	83.83	.355	− .001	
	22	14 52	39.23	.343	.000	
	22	15 57	40.32	.350	+ .006	
	23	14 43	63.08	.352	.000	
	23	16 01	64.38	.342	+ .008	
	23	17 07	65.48	.341	+ .026	
	29	16 39	18.93	.332	+ .015	
February	1	14 06	88.37	.348	+ .001	
	10	13 58	19.12	.345	+ .002	
	20	13 07	68.17	.337	+ .001	6 sets
	22	13 09	21.13	.345	+ .002	6 sets
	22	14 24	22.38	.366	+ .008	6 sets
	24	13 03	69.03	.349	+ .001	
	24	15 02	71.02	.320	+ .017	
March	2	14 24	24.28	.364	+ .013	6 sets
	14	13 17	26.03	.344	+ .013	4 sets
	14	14 08	26.88	.322	+ .030	4 sets
	22	13 33	28.20	.355	+ .023	

is that stars must be observed in succession rather than simultaneously, but I am sure that we have not reached the limit of accuracy attainable on good nights, or even on fair nights if the stars are close together.

In Table II are listed the observations of *β Aurigae* taken between September 20, 1910, and March 23, 1911. The times were reduced to the sun, and the phase based upon Baker's spectroscopic elements, from which the computed time of eclipse is 1910 October

21, $21^h\ 46^m$ G.M.T. The difference of magnitude is always in the sense: magnitude of *β Aurigae* minus magnitude of *β Tauri.* The correction in the absorption column has already been applied to the difference of magnitude. A set of measures comprises 6 exposures on the variable, and 4 on the comparison star, and near minima each tabulated difference of magnitude is the mean of 2 such sets, except as noted, while between minima each result is usually the mean of 5 sets.

Before the observations were completed, it became evident that the measures at large west hour angles gave residuals in one direction, proving that the average absorption correction was too small. This was investigated by first discussing those observations between minima where the correction was not more than 0.010 magnitude. These selected results were arranged according to phase and grouped into the normals of Table III. For this purpose the observations from 4 to 6 hours from minima were also used, as it was seen that the eclipses lasted only about 3 hours on each side of minimum. It was assumed that the two branches of the entire curve are the same, and one-half the period, or $47^h.52$, was subtracted from the phase of each observation following the second minimum. In Table III, the branch of the curve is indicated in the first column, and the last column gives the residuals from a comparison with the final light-curve.

TABLE III

NORMAL MAGNITUDES BETWEEN MINIMA, SMALL ABSORPTION

Branch of Curve	Phase	Difference of Magnitude	Absorption	O.−C.
		mag.	mag.	mag.
I, II.........	$5^h.89$	0.358	+0.001	+0.001
I............	8.85	.362	− .002	+ .006
II...........	10.43	.360	− .001	+ .005
II...........	15.13	.350	+ .004	− .001
I............	17.34	.350	− .003	.000
I............	20.91	.350	.000	+ .001
II...........	21.32	.343	+ .001	− .006
I............	25.46	.346	+ .002	− .002
II...........	27.01	.349	− .002	.000
II...........	31.20	.354	− .001	+ .003
II...........	39.33	.349	− .001	− .007
I............	40.32	.348	.000	− .009
I, II.........	42.76	.363	.000	+ .005

The magnitudes in Table III are practically free from the effect of absorption, and show a decided variation in the light of *β Aurigae* between minima, caused presumably by the two components being elongated in the line joining them. If we assume that each body is a prolate spheroid with major axis coincident with the line of centers, this variation may be expressed by the formula

$$J = J_0 \sqrt{1 - \epsilon^2 \sin^2 i \cos^2 \phi}\,, \tag{1}$$

where J is the light intensity at any instant, J_0 the intensity at maximum, ϵ the eccentricity of figure of the ellipsoids, i the inclination of the orbit, and ϕ the phase angle or true anomaly measured from minimum. For each normal magnitude of Table III, it is easy to compute the relative light, J, and then solve for the two unknowns J_0 and $\epsilon \sin i$, $\sin i$ being nearly unity; but in the present case it is sufficient to use the approximate relation

$$m = m_1 + \frac{c}{2}(1 - \cos 2\phi)\,, \tag{2}$$

where m is the magnitude at any time, m_1 the hypothetical magnitude at conjunction if there were no eclipse, and c the ellipticity of the spheroids, $c = \frac{a-b}{a}$ in an ellipse with semi-axes a and b. It is not necessary to convert magnitudes into light-intensities because of the convenient relation that 1 per cent change in light corresponds very nearly to a variation of 0.01 magnitude, more exactly 0.0108 magnitude. Each normal gives an observed m in (2), and forming 13 observation equations, then the normal equations, and solving, we have

$$\begin{aligned} m_1 &= 0.359 \text{ mag.} \quad \pm 0.002 \text{ mag.} \\ c &= 0.011 \qquad\quad \pm 0.003 \end{aligned}$$

This determination of c is the most difficult photometric measurement I have yet attempted, but there is no doubt that the observations show this ellipticity. On the basis of constant light between minima the residuals give $[vv] = 0.000488$, and the addition of the term in c reduces this to $[vv] = 0.000268$. The probable error of one normal magnitude of Table III is ± 0.003 magnitude, which is

sufficiently small to justify the attempt to evaluate the ellipticity. In view of all the facts we may adopt

$$c=0.01$$

without assigning a probable error.

The adopted light-curve between minima was computed from m_1 and c substituted in (2), and is shown in Fig. 1. Each magnitude of Table II was next compared with the curve, and it was found that the results with large absorption may be brought into accordance with the others by multiplying the correction by 1.35. Therefore all of the magnitudes in Table II were altered by the addition of 0.35 times the first absorption correction.

In Table IV are the adopted normal magnitudes, and in each case the absorption is the average total correction which has been applied. Near minima each of the normals is ordinarily the mean of 3 magnitudes of Table II, or a total of at least 6 sets of measures, while the normals between minima comprise about 15 sets. The last column gives the residuals from a comparison with the final computed light-curve.

Although a few of the normals comprise an extra number of sets, there seems no good reason for assigning them greater weight. Observers without experience with the selenium photometer can hardly realize the idiosyncrasies of this instrument. In most classes of work one measure is about equal to another taken under the same conditions, but with selenium if we assign weights inversely as the squares of the probable errors, we find that some observations should have at least 10 times the weight of others. The question is wholly the disturbance going on within the selenium, and it is not at all unusual to find the probable error of a single measure as small as 1 per cent, and then a few minutes later to see the errors rise to 2, 3, and occasionally 5 per cent. Again, it is evident that one observation with a clear sky is worth a score of measures taken through passing cloud, haze, or smoke, and though a most careful watch was kept of the sky, as well as of the successive galvanometer readings, it is almost certain that some of the measures are impaired by changes in the absorption. For these reasons I have not made a fine point of assigning weights, and the adopted normals between minima or near minima are considered as all about equally reliable.

TABLE IV

NORMAL MAGNITUDES NEAR MINIMUM I

Phase	Difference of Magnitude	Absorption	O.−C.
h	mag.	mag.	mag.
−4.31	0.355	+0.004	−0.003
−2.70	.381	+ .019	+ .017
−1.76	.391	+ .005	− .003
−0.68	.437	− .002	+ .008
−0.03	.422	− .002	− .013
+0.49	.431	− .001	− .001
+1.00	.415	− .001	− .006
+1.50	.396	+ .002	− .009
+1.80	.380	+ .004	− .013
+2.09	.394	+ .014	+ .012
+2.47	.371	+ .018	+ .001
+2.83	.369	+ .017	+ .009
+4.05	.366	+ .020	+ .008
NEAR MINIMUM II			
43.88	0.362	+0.004	+0.003
45.23	.352	+ .001	− .023
45.82	.387	.000	− .010
46.50	.435	+ .008	+ .014
46.97	.439	.000	+ .008
47.42	.436	+ .017	+ .001
47.98	.436	− .003	+ .004
50.12	.372	− .001	+ .005
51.90	.358	+ .014	.000
BETWEEN MINIMA			
8.85	0.362	−0.002	+0.006
17.28	.346	+ .002	− .004
19.84	.350	+ .001	+ .001
23.35	.356	+ .007	+ .008
27.67	.343	+ .022	− .006
40.32	.348	.000	− .009
56.66	.355	− .002	− .001
61.02	.357	+ .002	+ .004
66.01	.344	+ .016	− .006
70.26	.342	+ .006	− .006
76.34	.352	− .002	+ .003
81.73	.353	+ .008	+ .001
87.46	.349	+ .005	− .007

In general the observations during the eclipses were continued for many hours on a few nights, whereas the results between minima depend upon shorter periods of observing on a greater number of nights, and it is therefore impossible to make the entire series

homogeneous. Roughly speaking, each normal near minima is the result of something more than one hour's continuous observing, and between minima the normals represent about 3 hours of work. These happen to be the approximate times required for securing the similar observations of *Algol*, and it may be of interest to compare the probable errors of the previous work with those found from the residuals of Table IV.

TABLE V

	β Aurigae	*Algol*
	mag.	mag.
Probable error of a normal magnitude near minima	±0.007	±0.023
Probable error of a normal magnitude between minima	±0.004	±0.006

The Harvard magnitudes are *β Aurigae*, 2.07, *Algol*, 2.1; while the Potsdam values are *β Aurigae*, 2.21, *Algol*, 2.4; and therefore the new variable is slightly brighter than *Algol* itself, though not enough to increase the accuracy of the results. The larger errors near minimum for *Algol* were due to the greater diminution of light, and the residuals between minima depended upon a light-curve which is more complicated than that of *β Aurigae*. Nevertheless, it is certain that the present work represents a substantial increase in accuracy over the former, and this is especially true of the selected normals of Table III, where as noted the probable error is ±0.003 magnitude. The residuals which have been discussed were of course derived from the light-curve computed from the adopted elements, which we now proceed to obtain.

THEORY OF THE SYSTEM OF *β Aurigae*

We may assume without further argument that *β Aurigae* is an eclipsing system, especially since the observed minima agree closely with the times predicted from the spectroscopic elements. This star, the binary character of which was discovered at Harvard, has been studied spectroscopically for 20 years, and the results have been ably brought together and summarized by Dr. R. H. Baker.[1] As his results will be used from time to time in what follows, they are given here in such form as needed.

[1] *Publications of the Allegheny Observatory*, I, 163, 1910.

SPECTROSCOPIC ELEMENTS BY BAKER

$P = 3.960027$ days $+ 0.000010\ (t - 1906)$

$e = 0.00$

$T = 1905$ September 11.7324 G.M.T.

$(a_1 + a_2) \sin i = 11{,}981{,}000$ km

$$m_1 = \frac{2.21 \odot}{\sin^3 i}$$

$$m_2 = \frac{2.17 \odot}{\sin^3 i}$$

We are first concerned with the variable period, P. Since T refers to the passage of the more massive component through the ascending node, eclipse I will take place in the circular orbit at the time $T + \frac{P}{4}$. This time was brought forward to October 21, 1910, with the period 3.960052 days, and the light-ephemeris computed upon the basis of a present period, 3.960077 days. The phase of the photometric observations was reduced to the sun, though this correction was presumably neglected in deriving the spectroscopic elements. After plotting the normals of Table IV, I was quite unable to assign any time of minimum better than that predicted, any discrepancy being certainly not more than one- or two-tenths of an hour, and we may therefore conclude that the spectroscopic and photometric results are in entire accordance. Assuming Baker's period, the light-elements of *β Aurigae* are:

Minimum I = 1910 October 21, $21^h\ 46^m$ G.M.T. $+ 3^d\ 23^h\ 02^m\ 30^s7 \cdot E$
$= \text{J. D. } 2418966.907 + 3^d960077\ E$

Min. II − Min. I $= 1^d980 = 47^h52$,

where minimum I refers to the eclipse of the more massive component.

We have now to determine the elements of an *Algol* variable from an eclipse variation of less than 0.08 magnitude, which, to the writer at least, seemed a difficult task. It is interesting to note what might have been our conclusions concerning this system, if our eyes were, say, ten times as sensitive to light-changes, and this

variable had been discovered before the advent of the spectroscopic measures. Assuming a bright body and a small dark companion, the observations can be well represented by a period of revolution of 1.98 days and a radius of the satellite about 1/4 that of the primary. It is not probable that the approximate elements of other *Algol* variables are so much in error, for an eclipsing star with equal minima cannot have a range of more than 0.75 magnitude, and most of the *Algol* stars thus far discovered have a variation more than a whole magnitude.

It is evident that almost any hypothesis as to the relative radii can be made to fit the observations, but there are considerations which seem to show that the components are of the same size. The spectroscope reveals that the masses are nearly equal, also that the spectra are of the same type, and so nearly of the same intensity that various observers have made mistakes in identification. The photometric observations make the two minima equal within 0.01 magnitude, which means the same surface-intensity for either component. From the equality of the spectra we may conclude that the total light from each body is the same, and dividing total light by surface-intensity, the radii must be equal, within say 5 or 10 per cent. With this simplification of the problem, since the orbit is circular, the only elements to be found are a, the radius of the relative orbit, and i, the inclination. In all strictness the unit for a is the shortest radius of either body. Consider the projected disks, which are assumed as circular during an eclipse, and let

P = the period,
t = the time in hours from minimum,
ϕ = the true anomaly, counted from minimum,
θ = the projection of ϕ in the apparent orbit,
ρ = the distance between centers of the projected disks,
2η = the angle subtended at each center by the common chord,
M = the area common to the two disks,
J = the light sent to the earth, the unit being the sum of the total light of the two components.

To obtain preliminary elements we adopt a value for the light, J, at minimum, and also for the duration of the eclipse. Let a zero

subscript represent the value of each quantity at minimum, and ϕ_1 the value of ϕ at first or last contact, and we have for the determination of a and i:

$$
\begin{aligned}
2\eta_0-\sin 2\eta_0 &= M_0 = 2\pi\,(1-J_0)\ , \\
a &= \frac{2\sqrt{1-\cos^2\eta_0\,\cos^2\phi_1}}{\sin\phi_1}\ , \\
\cos i &= \frac{2\cos\eta_0}{a}\ .
\end{aligned}
\tag{3}
$$

The equations for the light-ephemeris from adopted elements are

$$
\begin{aligned}
\phi &= \frac{360^\circ}{P}\,t\ , \\
\operatorname{ctn}\theta &= \cos i\,\operatorname{ctn}\phi\ , \\
\rho &= \frac{a\sin\phi}{\sin\theta}\ , \\
\cos\eta &= \frac{\rho}{2}\ , \\
M &= 2\eta-\sin 2\eta\ , \\
J &= 1-\frac{M}{2\pi}\ ,
\end{aligned}
\tag{4}
$$

and the observation equations for the corrections, δa and δi, from the residuals, δJ, take the form

$$
\frac{\rho\sin\eta}{\pi a}\,\delta a-\frac{a^2\sin 2i\cos^2\phi\sin 2\eta}{2\pi\rho}\,\delta i=\delta J\ .
$$

As there are only two unknowns, the least-square solution is very easy.

Applying these equations to the case in hand, the normals near the two minima were combined into normals for a composite minimum, and the magnitudes were converted into observed light, J, the unit being the light for difference of magnitude, $m_1=0.359$. The eclipse was assumed to last 6 hours, or $\phi_1=11^\circ.36$, and the light at minimum, $J_0=0.930$. The values of a and i thus derived were seen to be very close to the best that the data would yield, but the corrections δa and δi were computed from (5), and the two sets of elements are in Table VI.

TABLE VI

ELEMENTS OF β *Aurigae*

	I	II
a............	6.83	6.86 ± 0.35
i............	$77^\circ.22$	$77^\circ.19\pm0^\circ.48$
$[vv]$..........	0.000453	0.000392

The weights and probable errors of a and i were computed in the usual way from the coefficients of the normal equations, and the final residuals.

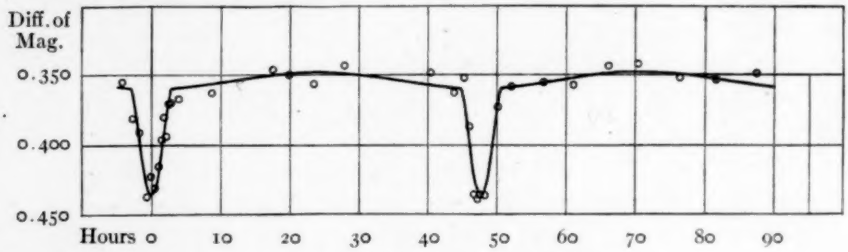

FIG. 1.—The light-curve of β *Aurigae*

The next step was to compute the light-curve during eclipse, and this is given in Table VII, together with that part of the curve between minima which was previously derived. The computed duration of each minimum is $5^h.90$, and since the two branches of the curve are assumed to be identical, the phase for the second half is obtained by adding $\frac{P}{2}=47^h.52$ to the phase in the table.

TABLE VII

LIGHT-CURVE OF β *Aurigae*

PHASE	DIFFERENCE OF MAGNITUDE		PHASE	DIFFERENCE OF MAGNITUDE	
	From β *Tauri*	From Minimum		From β *Tauri*	From Minimum
h.	mag.	mag.	h.	mag.	mag.
±0.0.......	0.435	0.000	10.0.......	0.355	0.080
±0.5.......	.432	.003	15.0.......	.351	.084
±1.0.......	.421	.014	20.0.......	.349	.086
±1.5.......	.405	.030	23.76......	.348	.087
±2.0.......	.385	.050	25.0.......	.348	.087
±2.5.......	.369	.066	30.0.......	.350	.085
±2.95......	.359	.076	35.0.......	.353	.082
$+5.0$.......	.358	.077	40.0.......	.357	.078

This light-curve is shown in Fig. 1, where each plotted circle represents a normal magnitude of Table IV.

COMPARISON WITH THE SUN

From the spectroscopic data it is a simple matter to express the dimensions of β *Aurigae* in terms of the sun, whose radius is taken as 695,000 km. From $i=77^\circ.19$ the true value of a_1+a_2 is 12,280,000 km, from which follow the quantities in Table VIII.

TABLE VIII

R	Radius of each component	2.58 ☉
m_1	Mass of first component	2.38
m_2	Mass of second component	2.34
d	Density of each component	0.14

These results show nothing extraordinary about the system of β *Aurigae.* The radii and masses are not extreme, and the density is comparable with that of other *Algol* stars. It should be noted that the mean density, 0.14, follows also from the light-curve without reference to the spectroscopic measures.

We are now ready to consider what is perhaps the most important element of all, the surface-intensity of each component. This requires a knowledge of the absolute annual parallax of β *Aurigae*, and in Table IX are the results adopted by Kapteyn and Weersma.[1]

TABLE IX

PARALLAX OF β *Aurigae*

Observer	π	Weight
Flint	0".000	2
Tikhoff	+0".023	3
Adopt	+0".014	

This small parallax is perhaps confirmed by the researches of Hertzsprung[2] and Ludendorff[3] on the extended system of *Ursa Major*.

[1] *Publications of the Astronomical Laboratory at Groningen, No. 24,* 1910.

[2] *Astrophysical Journal,* **30**, 135 and 320, 1909.

[3] *Astronomische Nachrichten,* **183**, 113, 1909.

Ludendorff derived from the proper motion of *β Aurigae* the parallax, $\pi = 0''.023$, and from the radial velocity, $\pi = 0''.019$. Of course these values of the parallax depend upon the assumption that *β Aurigae* is moving parallel to and with the same velocity as the other members of the group. It would be interesting indeed if we could generalize as to the characteristics of the others from the results for *β Aurigae*, but this star is quite isolated from the remaining members, having the least parallax, and the greatest computed luminosity of all.

We might adopt $\pi = 0''.02$, but it seems better to assign $\pi < 0''.03$ and compute the lower limit of luminosity from the equation

$$\log 2l = -2 \log \sin \pi - 0.4\,(M-S)\,,$$

where l is the luminosity or total light of each component, π the parallax, M and S the stellar magnitudes of the star and sun, which we adopt as 2.07 and -26.6 respectively. Representing the surface-intensity of each body by σ, there follows

$$l > 80\odot\,,$$
$$\sigma > 12\odot\,,$$

or, roughly speaking, each component of *β Aurigae* emits per unit area almost certainly more than 12 times, and possibly 25 times as much light as the sun. To test this result, the parallax corresponding to $\sigma = \odot$ was computed, and found to be $\pi = 0''.104$. We may therefore conclude definitely that each component of this star, which is of spectrum Class A p, is very much more intense than the sun. This is not surprising, for there is evidence that the same thing is true of the brighter component of the *Algol* system. According to current theories of stellar evolution perhaps we should expect the surfaces of Sirian stars to be of greater intrinsic brilliancy than the surfaces of solar stars—the position of the maxima in the spectral energy-curves seems almost conclusive evidence on this point; but it is nevertheless desirable to check theory by observation wherever possible.

In the foregoing calculations it has been tacitly assumed that each component is uniformly intense over its entire surface, but it is

evident that no such uneven illumination could be detected as that found for the companion of *Algol*. There was the possibility that the discovery of the secondary minimum of *Algol* with the selenium photometer may have been due to the extra sensibility of selenium to the light of a red star, but in the present case of β *Aurigae*, where the minima are equal, we should expect the range of magnitude to be quite independent of the wave-lengths by which the instrument is affected.

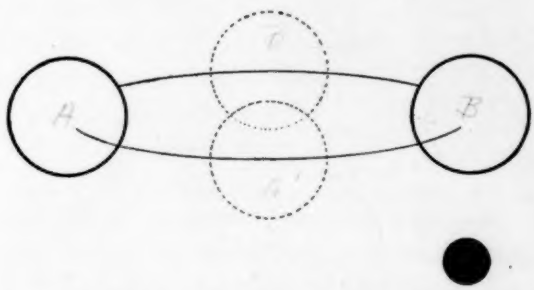

FIG. 2.—The System of β *Aurigae* as viewed from the earth.

Fig. 2 shows the system of β *Aurigae* as viewed from the earth, and for comparison the sun has been drawn to scale and as a dark body. The ellipticity of figure, $c=0.01$, is not discernible to the eye, and the masses are so nearly equal that the two components are represented as moving in the same orbit.

SUMMARY

1. It has been found that β *Aurigae* is an eclipsing variable star which is brighter than *Algol* itself. The variation caused by eclipses amounts to 0.076 magnitude, with an additional change of 0.011 magnitude due to the ellipticity of figure of the two components, making a total range of 0.087 magnitude.

2. Within the limits of observational error, the times of light-minimum are in exact accordance with the times predicted from the spectroscopic elements by Baker.

3. The principal facts concerning this system are:

From the Light-Curve

	Radius of each component	1.00
a	Distance between centers	6.86 ± 0.35
c	Ellipticity of figure	0.01
i	Inclination of orbit	$77^{\circ}19 \pm 0^{\circ}48$
P	Total period	$95^{h}04$
	Duration of each eclipse	$5^{h}90$

From $\pi < 0''03$, Sun $= -26.6$ Mag., β *Aurigae* $= 2.07$ Mag., $(a_1+a_2) \sin i = 11{,}981{,}000$ km

R	Radius of each component	$2.58\odot$
m_1	Mass of first component	2.38
m_2	Mass of second component	2.34
d	Density of each component	0.14
l	Total light of each component	$>80.$
σ	Surface-intensity of each component	$>12.$

4. The determinations of parallax make it seem certain that the components which are of spectrum Class A p, have each a surface-intensity many times greater than that of the sun.

I am indebted to Mr. Percy F. Whisler for most efficient assistance in making all of the observations of β *Aurigae*, and also to the Rumford Committee of the American Academy of Arts and Sciences for successive grants of \$350 and \$200 in support of this and other work with the selenium photometer.

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Urbana, Ill.
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OTION AND CONDITION OF CALCIUM VAPOR OVER SUN-SPOTS AND OTHER SPECIAL REGIONS. II

By CHARLES E. ST. JOHN

PROMINENCES IN PROJECTION

Occasionally spectrum plates have been obtained in which the K absorption line has shown extraordinary appearances. These have been obtained at various times, and sometimes by successive exposures near the same point of the solar surface, so that the reality of the appearances is well established and the phenomena which they represent must be of quite frequent occurrence in the sun. The data for the plates showing such peculiarities are given in Table X.

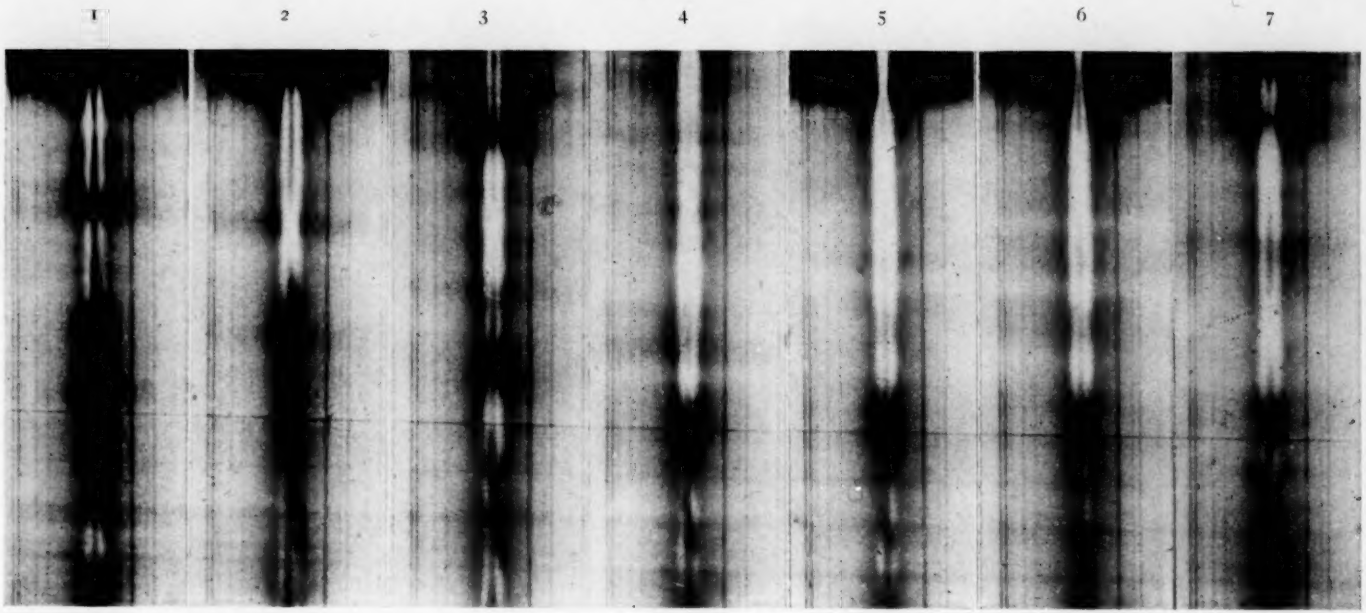
The characteristic appearance in each case upon which the present interpretation is based is the undisturbed condition of the absorption line K_3. This occupies its usual position, as shown by its wave-length agreeing with the normal value for this part of the disk, and is bounded on the red and violet edges by the emission line K_2. In some cases the violet component of K_2 shows a narrow absorption line superposed upon it through a distance of some millimeters. In other instances there is a broad absorption line on the violet side of the emission line. The approximate wave-length of this abnormal line shows a high ascending velocity in the vapor to which it is due. From the fact that the ordinary absorption line is undisturbed it appears that the phenomena here manifesting themselves by the displaced absorption line originate in great masses of calcium vapor having no direct connection with those levels of the solar atmosphere where the ordinary absorption line is produced and moving independently of that part of the atmosphere. That is, they are detached masses of vapor, such as prominences on the solar hemisphere turned earthward would present. The phenomenon bears a certain analogy to that observed by Frost and by Slipher in the spectra of spectroscopic binaries in which the H and K lines were undisplaced, and of which the suggested interpretations are an extended atmosphere of

TABLE X

ABNORMAL K LINE OVER SPECIAL REGIONS

Plate	Date	Normal K_3 Line	Abnormal K Line	Velocity of Ascent	Remarks
	1909			km	
216......	Jan. 19	3933.675	3933.464	15.5	V K_2 double over a region of the solar surface 50,000 km in extent. K_3 undisturbed. Bounded by the bright components of K_2. 50 mm from the East limb
226......	Jan. 20	.680	.470	15.0	V K_2 double over a region 100,000 km in extent. K_3 regular and undisplaced. 50 mm from East limb
247......	Jan. 29	.683	....	....	2 mm steps from east to west. Over dark hydrogen flocculus north of spot 6608. Exposure 2, normal conditions
247......	Jan. 29	.679	....	....	Exposure 3. R K_2 partially washed out on red edge. V K_2 broad. K_3 sharply bounded on V K_2 side. Faintly bounded by R K_2
247......	Jan. 29	.679	.484	13.9	Exposure 4. V K_2 broad. Divided by absorption line. K_3 undisturbed and bounded by the two components of K_2
247......	Jan. 29	.681	.412	19.4	Exposure 5. K_3 undisturbed. Bounded by K_2 on both edges. Broad dark line to the violet of V K_2
247......	Jan. 29	.678	.349	24.2	Exposure 6. K_3 undisturbed. Bounded by K_2. Broad dark line to violet of V K_2
247......	Jan. 29	.681	.378	22.0	Exposure 7. K_3 undisturbed. Extraordinary absorption line similar to exposure 6.
257......	Jan. 30	.676	.456	16.1	Exposure 1. V K_2 double over region of solar surface. 15,000 km in extent. K_3 undisturbed. Bounded by K_2 on each edge
257......	Jan. 30	.670	.467	15.2	Exposure 2. 15,000 km west of Exposure 1. V K_2 double over region 35,000 km in extent. K_3 undisturbed. Bounded by K_2 on both edges
276......	Feb. 22	.684	.466	15.3	V K_2 double over a region 80,000 km in extent. K_3 undisturbed. At center. Time 10 A.M.
286......	Feb. 22	.676	.460	15.8	Same region as in No. 276, but 4 hours later

PLATE VIII



THE K LINE OF CALCIUM AT 2 MM INTERVALS IN THE NEIGHBORHOOD OF A DETACHED MOVING MASS OF VAPOR

Enlargement: 5 times from original negative with 18-foot spectrograph and Snow telescope. 1909, January 29

Exposures 1, 2, Normal condition

Exposures 5, 6, Abnormal absorption line to the violet of and distinct from K_3

calcium surrounding the system or detached masses of calcium vapor in space. Plate VIII is a reproduction of a photograph taken with 2 mm steps over such a moving mass. It is possible to see in the upper third of the reproduction, on exposures 5, 6, and 7, the characteristics referred to: the undisturbed K_3 line, the two components of the K_2 line, and the absorption line displaced to the violet. A fine example of this effect is shown in the beautiful reproduction, Plate 46, of the Meudon *Annales*, Tome IV. Under the title "Sur un filament extraordinaire,"[1] MM. Deslandres, d'Azambuja, and Burson report on this interesting case in which the displacements indicated vertical velocities exceeding 100 km per second. The phenomenon was of short duration, ending an hour and a half after the maximum velocity had been gained. It was not attributed to a prominence viewed in projection against the disk, but otherwise the interpretation,

> Tout se passe comme si, la couche K_3 restant à peu près dans son état ordinaire, une grande masse de gaz au-dessus, distincte de la première, s'élevait irrégulièrement à de grandes vitesses,

is the same as that given here.

It seems more than probable that the dark flocculi or *filaments* are closely connected with prominences when the remarkable Plates 43 and 45, Tome IV of the Meudon *Annales*, are examined. These reproduce K_3 spectroheliograms taken four days apart, upon which a long, dark flocculus, or chain of such, extends across the southern hemisphere of the sun. On Plate 43, where the dark flocculus reaches the east limb, it appears to blend into a large prominence, and at the west limb at the point touched by the flocculus, a small prominence is shown. On Plate 45, taken four days later, the flocculus has advanced from the east limb and the associated prominence has disappeared, while at the west limb the prominence has increased in height and appears still on the line of the dark flocculus. The whole appearance is as if the dark flocculus were a mass of calcium vapor high above the chromosphere, revealing itself on the disk by absorption and at the east and west limbs as prominences. Such masses of calcium vapor would be expected, under this point of view, to show as they do at times

[1] *Comptes Rendus*, **150**, 1638, 1910.

the enormous upward velocities obtained in the case of prominences. As the projected masses settle back again the motion would be slower. Measurements of the K_3 line over such a dark flocculus appearing on the *Ha* spectroheliogram of August 4, 1910, gives over the flocculus λ 3933.681, and around the flocculus λ 3933.675, indicating a downward movement in both cases which was slightly greater over the region of greater absorption. The same point of view is held by Mr. Michie Smith, who states that these dark calcium flocculi when photographed near the limb are found to agree in position with the prominences.[1]

Mr. Evershed[2] considers the very conspicuous dark flocculus shown on certain H_2 spectroheliograms taken at Kodaikânal, Feb.–Apr. 1910, as due to absorption produced by the extensive prominence then transiting the sun's disk, and says:

> When these dark markings are seen extending to the sun's limb they are found almost invariably to end in a prominence, but the latter in many cases are somewhat insignificant in height.

The detailed spectrographic study of such regions of absorption is a part of the program at Mount Wilson.

DISCUSSION

The evidence for and against general or local systems of circulation of the chromospheric calcium vapor deduced from the data of this paper may be considered from the point of view of the absorbing and emitting layers separately and together. In the case of the absorbing vapor the wave-length measurements over possibly related regions are:

At the center	3933.680 (63)[3]
Circumfacular regions	.678 (134)
Flocculi	.679 (176)
Penumbrae	.681 (120)
Umbrae	.681 (11)
In the arc	.667[4]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 25, 7; *Astrophysical Journal*, **27**, 225, 1908.

[2] *Astrophysical Journal*, **33**, 6, 1911.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 41, 1910; *Astrophysical Journal*, **32**, 76, 1910.

[4] *Contributions from the Mount Wilson Solar Observatory*, No. 44, 10, 1910; *Astrophysical Journal*, **31**, 152, 1910.

The most striking feature of the assembled data is the remarkable agreement of the separate means with the general mean 3933.679 from five hundred separate exposures. It appears that on the whole the high-level calcium vapor of the chromosphere is descending over these different regions of the solar surface with a surprisingly uniform velocity on the average. In seeking for the source of supply we may look to outer space as Professor Newall has suggested, or to the inner regions of the sun. In speaking of the possibility of attributing the main characteristic spectroscopic phenomena of the sun to matter constantly streaming in from without Professor Newall[1] says:

> We may divide the attracted matter into three categories: (I) molar matter, in masses large enough to be drawn in in spite of light-pressure, having diameters longer than about 2½ times the wave-length of light; (II) molecular matter, in masses small enough to escape, in virtue of the diffractional effects, the repulsion of light, having diameters less than about one-tenth of the wave-length of light; and (III) light-driven matter, in masses intermediate between molar matter and molecular matter, and subject to the repulsion of light.
>
> The reversing layer of the Sun is provided by molecular matter, constantly streaming across what we may call a critical envelope concentric with the Sun, and probably is in a slightly modified state of radiative equilibrium. The constant flux of matter here involved is provided by those constituents of the planetary whirl of molecular matter circulating round the Sun, which are directed inwards upon the Sun in virtue of properly directed collisions.

If there were no evidence of any source of supply from the inner regions of the sun, the practical agreement of the mean velocities of the descent of the absorbing layer of calcium over such diverse regions of the solar surface as those over which the above measurements were made might well be adduced as tending to support the hypothesis of a constant influx from outer space. The rotation of this absorbing layer shows a small polar retardation and a high equatorial velocity relative to the reversing layer, but still an organized rotation of low value compared to planetary velocities. There is evidence, however, that calcium vapor is rising from the interior over the general surface of the sun and over particular regions. As previously quoted in this paper from *Contribution* No. 48 the measurements of the wave-length of the K_2 line of cal-

[1] Newall, Presidential Address, *Monthly Notices of the Royal Astronomical Society*, **69**, 343, 1909.

cium due to emitting vapor was found to be 3933.641 Å over the general surface of the sun as against 3933.667 Å in the arc, indicating a mean upward velocity of 1.97 km per second. This vast ascending mass of calcium vapor would seem to be sufficient for the continual renewal of the supply, though perhaps in a less simple manner than the inflow from outer space. Over limited but still extensive areas of the solar surface great masses of relatively cool calcium vapor are ascending with very high velocity. These have been attributed to prominences seen in projection. These masses of vapor must diffuse laterally and eventually return to the solar surface under the action of gravitation, being free from the effects of light-pressure owing to their molecular condition. The supply from this source, probably having its origin in eruptions of much denser vapor from the interior, would hardly account for the layer of absorbing vapor enveloping the whole sun. This finds a sufficient and more probable supply in the vapor producing the K_2 line of calcium which is ascending over the general surface.

The quantitative data with a bearing upon a circulation of the calcium vapor shown by measurements of the K_2 line are the wave-lengths of this line over particular regions as shown below:

Over general surface.......	3933.641 (20)[1]
Over flocculi............	.664 (175)
Over penumbrae..........	.665 (120)
Over umbrae............	.682 (141)
In the arc...............	.667

This shows a rise of emitting vapor over the general surface with a velocity of 1.97 km per second and a descent of this vapor in the umbrae of spots with a velocity of 1.3 km per second, a total range of 3.27 km per second. The condition over the flocculi indicated by these measures is an intermediate one, possibly, on the whole, one of slow ascent. Taken in connection with the inflow shown in Table VII (p. 75) the evidence for a system of circulation of the emitting vapor is quite complete, in which the supply of vapor descending in the umbrae of spots is that rising mainly from the immediate surroundings of the flocculi and their peripheral portions and flowing toward the umbrae where it is drawn suddenly and rapidly inward.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 21, 1910; *Astrophysical Journal*, **32**, 56, 1910.

Attention has been called to the difference between the velocities of inflow and rotation obtained from wave-lengths of the K_2 and K_3 line. The results from Tables VII and IX are:

	K_2	K_3
Inflow........	1.24 km	2.00 km
Rotation......	0.98	1.59

Everything occurs as though the disturbance begins in the upper layer of the chromosphere and works down into the emitting layer, to which it communicates a motion of inflow and rotation, the lower stratum always lagging behind the upper. In the great majority of cases the K line over the umbrae is bright and single, but on a few plates taken even when the seeing was excellent the absorption line K_3 is present, while on later plates of the same spot it had disappeared. In such a case the presence of the absorption line cannot be due to photospheric light falling upon the slit of the spectrograph. The absorption line appears to be at times a real spot phenomenon and there is some evidence that it belongs to the earlier life history of a spot.

Some light is thrown upon the bright reversal of the K line over the umbrae of spots by comparing the relative intensities of the umbral line and the K_2 and K_3 components over the penumbrae. For this purpose there was at hand the photometer devised by Hartmann[1] for the measurement of the intensities of photographically blackened surfaces. This enables one to isolate an extremely small portion of the surface and to match its intensity against the photographically produced wedge. The measurements are given in Table XI, in divisions of the wedge-scale, which increase with increasing density in the negative.

A striking result is the relatively weak intensity of the bright umbral line compared with that of the K_2 and K_3 components immediately outside the umbra. Under ordinary visual examination of the negatives one gets the impression that the umbral line is much brighter than K_3 and almost equal in brightness to K_2 while in fact it is slightly less bright than K_3 on the average (Plate V, *a*). The dark background of the umbra brings the line into high relief,

[1] *Astrophysical Journal*, **10**, 321, 1899.

just as in the laboratory experiments on the sodium reversal the line appears to decrease in brightness on passing from the dark background to the intense continuous background of the arc. Since the temperature of the spot umbra is lower than that of the surroundings, the bright umbral line is probably produced by the same vapor as that to which the K_2 line is due, there being a continuous flux of the vapor into the umbra. The line is narrower and less bright than the K_2 line over the flocculi and penumbra, as

TABLE XI

RELATIVE INTENSITIES OF THE COMPONENTS OF THE K LINE

Over Umbrae			Over Penumbrae	
Reversal	V K_1	R K_1	K_2	K_3
40.4	28.1	27.5	45.4	43.2
35.6	25.7	26.3	45.6	41.2
48.1	37.2	36.8	58.9	53.1
47.0	36.0	35.1	55.2	48.0
41.1	28.2	28.3	46.3	41.2
44.4	29.5	29.6	57.1	....
44.9	28.5	28.3	46.2	44.0
49.6	30.2	29.7	56.0	48.4
50.9	47.3	47.0	66.4	50.3
44.7	32.3	32.1	53.0	46.5

would naturally follow from the diminished pressure and lower temperature obtaining at the center of the spot vortex. The resulting fall in the temperature of the absorbing vapor in the spot umbrae would reduce its radiation below that of the vapor to which the umbral line is due, as the bright line is frequently double the width of the K_3 line, and not always less intense as may be seen from the last three lines of Table XI. Therefore, it does not seem probable that the upper layer of calcium plays an important rôle in the production of the reversal. The absence of the K_3 line over the umbrae may be due to the diminished quantity of the absorbing vapor which was earlier drawn inward, while that supplied by the lateral inflow mainly descends in the region of the penumbrae and fails to reach the umbral region in large quantity during periods of rapid downdraught.

Plate V (*a*) reproduces the typical condition over spot umbrae, though in many cases the reversal is relatively more intense than

here shown. The curve (*c*) in Fig. 2 is drawn from the data in Table XI and represents the K line over the umbra of a spot. The widths of the K_2 and K_3 lines in Fig. 2 are drawn to scale and show the relative widths under the different conditions to which the curves refer, but the width of the K_1 line is only suggested. The ordinates of the curves reproduce the relative intensities of all the components in terms of the wedge-scale. The intensities of the absorption line on the two sides of the reversal as shown by these measurements are practically equal, individually, and on the average. Jewell[1] found that:

> The absorption toward the red from the reversal was considerably darker and broader than toward the violet, thus giving evidence of considerable relative velocity between the emission line and the broad absorption line or shading.

The present measurements show that the bright umbral line is shifted to the red, which would tend to cause the absorption in the K line to be more conspicuous toward the violet. A compensation might result from the displacement of the center of gravity of the K_1 line also to the red owing to the greater pressure under which the line is produced.

The inflow of the calcium vapor and the downdraught in the umbrae appear to be the usual condition of the spot, but the penumbral or extra-penumbral vortex is not developed around every spot, nor does it always persist in the case of a given spot when once developed. This is in harmony with the visual observations of Secchi, who considered the vortex an exceptional case:

> Si cela arrive quelquefois, c'est assez rare, car, sur trois cents taches et plus qu'on observe dans le cours d'une année, il y en a sept ou huit seulement qui présentent d'une manière bien tranchée la structure spirale qui devrait caractériser les tourbillons. . . . . Non seulement les taches ne présentent pas toutes la forme de tourbillons, mais, de plus, cette forme, lorsqu'elle existe, ne persiste pas plus d'un jour ou deux, tandis que les taches elles-mêmes peuvent subsister longtemps encore après avoir perdu la forme spirale.[2]

The spiral structure is not shown around all spots on the $H\alpha$ spectroheliograms, though the spots themselves are magnetic fields as evidenced by the Zeeman effect. It is probable that in many

[1] *Astrophysical Journal*, **3**, 105, 1896.

[2] Secchi, *Le Soleil*, Part I, p. 89.

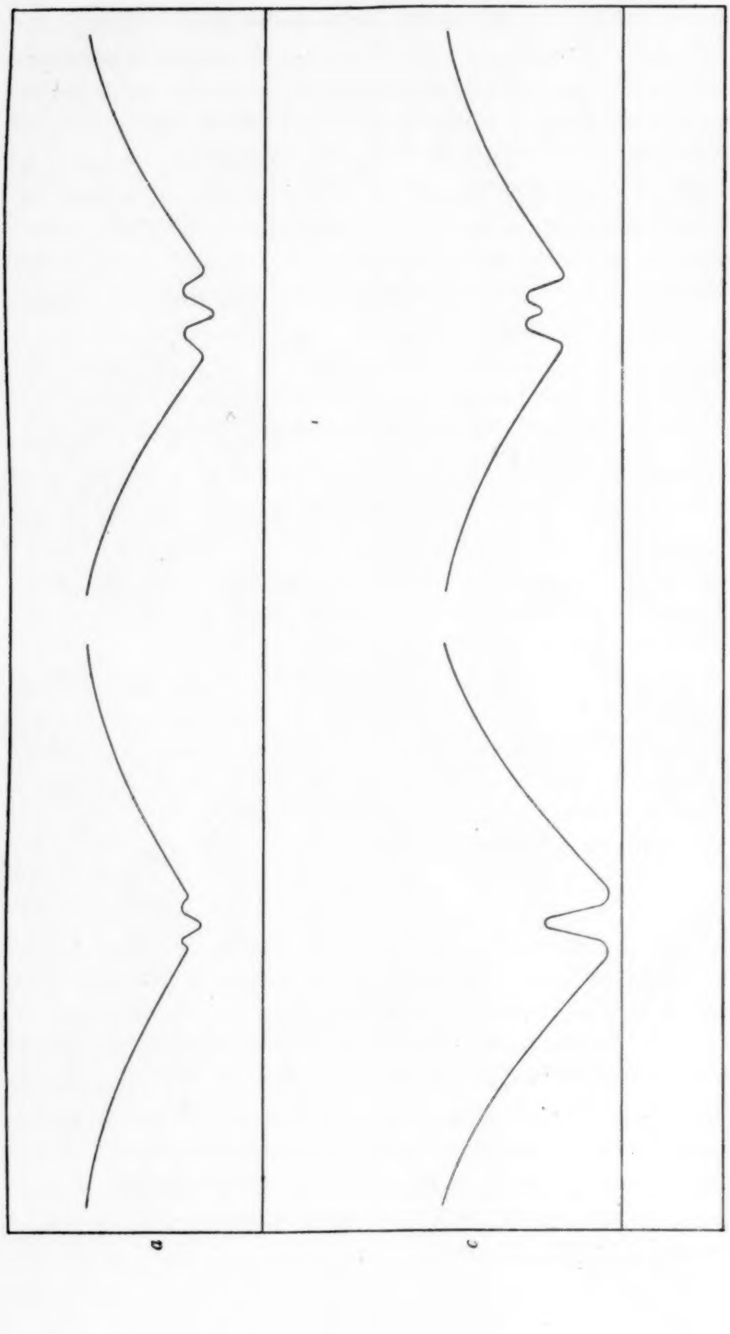


FIG. 2.—Relative intensities of the components of the K line of calcium

a, At the center of the solar disk
b, At the sun's limb
c, Over sun-spot umbrae
d, Over flocculi

instances the region throughout which the vortex is strongly developed does not extend very far outside the umbra, and the surrounding gaseous masses are not sufficiently involved to be arranged in stream-lines. It is surprising that, in view of the spectroscopic evidence of the inflow and downdraught of the calcium vapor, spectroheliograms taken with the H and K lines do not show more indication of stream-lines which are sometimes such marked features over vast areas of the $H\alpha$ spectroheliograms. This may be due to calcium vapor being present in broader and more continuous masses over the flocculi, and being more uniformly distributed around spots than the hydrogen. If an electro-magnetic instead of a hydrodynamic cause be assumed for the line-of-force structure on $H\alpha$ images, a suggestion made by M. Deslandres may be the key to the explanation:

> Chaque ion solaire mobile subit le champ électrostatique et électromagnétique de tous les autres. Comme l'effet n'est pas le même pour les atomes des masses différentes, on aurait là une explication des différences que présentent les images du calcium et d'hydrogène dans l'atmosphère solaire.[1]

Stream-line structure does occasionally occur on H_2 spectroheliograms according to both Hale and Evershed. In speaking of this Hale says:

> We have seen, however, that apparent lines of force having about the same curvature as the dark $H\alpha$ flocculi are frequently shown by H_2 between spots of opposite polarity, though this line fails to give most of the finer details of the $H\alpha$ structure. The difference may be due in large part to the greater effect of convection currents at the H_2 level.[2]

And Evershed writes:

> In good spectroheliograph plates of the calcium flocculi the regions of the penumbrae in quiet spots often show radial stream-lines and these are sometimes curved. In general, however, the more brilliant masses of flocculi of the surrounding region show no tendency to either a radial or a spiral structure.[3]

RELATIVE INTENSITIES OF THE K LINES

In the study of the conditions which produce the complex constitution of the H and K lines it appeared probable that a knowl-

[1] *Comptes Rendus*, **150**, 72, 1910.

[2] *Publications of the Astronomical Society of the Pacific*, **22**, 77, 1910.

[3] *Monthly Notices of the Royal Astronomical Society*, **70**, 224, 1910.

edge of the relative intensities of the components of the K line would be useful, and particularly the intensity of K_2 in comparison with the intensity of the continuous spectrum in the case of the very brilliant flocculi. For this purpose the Hartmann photometer was found very convenient and satisfactory.

One of the most striking appearances in a series of exposures extending from the limb to the center of the sun in which the exposure-times are such as to give equal intensities for the continuous spectrum is the great intensity of the K_2 components at the limb, and their gradually decreasing intensity with increasing distances from the limb. At the limb these components are very conspicuous, while at the center they are apparently very weak, except over flocculi, but still distinctly visible. Two typical plates were selected from a long series, upon which the intensity of the K_1, K_2, and K_3 lines was measured with the mean results in Table XII, which are expressed in divisions of the wedge-scale and represent the ordinary conditions at the center and limb of the sun.

TABLE XII

RELATIVE INTENSITIES OF THE K LINE AT LIMB AND CENTER

Plate	Position	K_1	K_2	K_3	K_2-K_1	K_2-K_3	K_1-K_3
329	Center	54.1	54.9	50.6	0.8	4.3	3.5
462	Limb	50.4	54.8	47.9	4.4	6.9	2.5

Two points revealed in obtaining this series of measurements are surprising, namely: the equal intensities of the K_2 line at the limb and center, and the difficulty of detecting with the photometer the difference between K_2 and K_1 at the center. When the lines are all in the field of view of the photometer, the K_2 line is distinctly seen and the dissymmetry of its components is clearly apparent, but when a small portion of the K_2 line is isolated by the photometer and settings of the wedge have been made for equality, it is very difficult to observe any change when the inner edge of the K_1 line is brought into the field of view. The results given in the table are the means of many settings. The apparent brightness of the K_2 line at the center is due largely but not entirely to contrast effect owing to the proximity of the strong absorption line K_3.

The increased intensity of the K_2 line at the limb is mainly apparent. The absolute intensities on these limb and center plates were practically equal, but the contrast effect at the limb was greatly increased by the greater strength of the absorption lines K_1 and K_3 between which the K_2 components lie. The effect is also enhanced by the greater width of the lines at the limb. In the cases of K_1 and K_3 the absorption at the limb, as would be expected from the greater effective depths of the absorbing layers, is greater than at the center for each line. But the increment in the case of K_1 exceeds that in the case of K_3, as they have become more nearly equal. At the center the K_2 line is just measurably brighter than the background produced by the K_1 line. At the limb the darkening of the background, particularly in the case of K_1, raises the K_2 line into relief without any great increase of its intensity. The results are shown graphically in Fig. 2, (*a*) at the center, (*b*) at the limb. The dissymmetry of the components of the emission line at the center is a marked feature, V K_2 being broader than R K_2. At the limb the components are equal in width and intensity. The curves are to scale and represent the relative widths of K_2 and K_3 and the relative intensities of all three components.

When the slit of the spectrograph crosses the very brilliant flocculi the density of the emission line K_2 appears to the eye, sometimes, to equal the density of the continuous spectrum. The photographic intensity of the spectrum decreases rapidly just beyond the K line due to absorption in the ultra-violet region by the glass of the lens. It was thought possible that the instrumental absorption might so reduce the intensity of the continuous spectrum on the violet side that a false result might be obtained if that alone were used. Comparison points were therefore taken on both sides of the K line at distances of about 12 Å with the following results expressed in the wedge-scale:

TABLE XIII

K_2 COMPARED WITH CONTINUOUS SPECTRUM

Plate	λ 3920	K_1	K_2	λ 3945	Continuous-K_2
197	69.5	39.3	59.2	70.7	10.9
267	59.5	28.6	48.5	60.9	11.7
296	57.6	39.2	51.2	58.2	6.7

In each case the intensity of the strong emission line was markedly less than that of the continuous spectrum even on the violet side. The usual calcium spectroheliogram is taken with H_2 or K_2, using one or both components, upon which the flocculi appear bright against the less intense background produced by the ordinary intensity of the line. The strength of the absorption line photographed with a long slit varies greatly along its length, becoming less intense as an absorption line when the slit crosses a flocculus, under which conditions it approaches the brightness of the emission line and may even disappear as an absorption line. The measurements in Table XIV were made at 2 mm steps along the line, including in the range of measurements two small flocculi.

TABLE XIV

INTENSITIES ALONG THE K_3 LINE

			Over Flocculus						Over Flocculus			
K_3	49.5	54.9	60.3	63.6	62.0	60.9	53.2	51.7	56.4	60.7	56.2	51.1
K_2	....	....	62.8	66.4	62.9	....	....	....	....	62.7	....	....

As seen, radiation has increased over the flocculi in both the K_2 and K_3 lines. The curve, (*d*), Fig. 2, shows the cross-section of the K line over such a flocculus. In comparing the ordinates of this curve with those of (*a*), it is seen that the radiation in the case of all three components has increased, the increase being the greatest for K_3. Spectroheliograms taken with the K_3 absorption line should show areas of great relative intensity corresponding to the flocculi shown on K_2 spectroheliograms; owing to the brightness of the K line over the umbrae, spots should not in general appear; and the dark flocculi, due to masses of absorbing vapor high above the chromosphere, should be much more conspicuous features than upon the K_2 spectroheliogram, since this cooler vapor, unless in very rapid motion, would greatly increase the absorption at the center of the K_3 line and affect the K_2 components in less degree. In speaking of the possible photography of the disk with the K_3 line Hale and Ellerman say:[1]

> If successful, photographs taken in this way will probably show the calcium prominences as dark regions projected upon the disk.

[1] *Publications of the Yerkes Observatory*, **3**, Part I, p. 19.

These are the appearances found by M. Deslandres in his skilful application of the spectroheliograph to work with the K_3 line:

Cette couche supérieure, étudiée avec le calcium et l'hydrogène a comme caractères; l'extension jusqu'à elle des facules de la surface, mais avec des formes différentes, la disparition presque absolue des taches et l'apparition des lignes noires, souvent très longues, qui sont les filaments.[1]

THE EMISSION LINE K_2

There is complete consensus of opinion in the case of K_3 namely: that it is produced by absorption in the upper and cooler regions of the chromosphere. As to the bright reversals H_2 and K_2, Hale and Ellerman say:

From a strict application of Kirchhoff's law it would appear that the calcium vapor in the lower chromosphere is actually hotter than the calcium vapor which lies above and below it. It seems improbable that the law can be rigorously applied in this case, and hence it may be necessary to attribute the strong radiation of the intermediate layer to causes other than temperature alone.[2]

Mr. Evershed speaks of the bright H_2 and K_2 lines as representing the emission of the relatively hot calcium vapor rising immediately above the ordinary faculae.

And Hale, in his *Stellar Evolution* (p. 86), says:

The bright H and K lines, referred to in the last paragraph, were found in close association with the faculae, and it appeared probable that much of the highly heated calcium vapor, to which these bright lines are due, rises from the interior of the Sun through the faculae.

M. Deslandres considered the light of the chromosphere to have an electric origin and wrote of the brilliant flocculi overlying the faculae:

Dans la chromosphère, les phénomènes électriques sont plus intenses au-dessus des points élevés de la surface.[3]

And later he has attributed the increased radiation over the bright regions to the compression produced by the descent of the vapors from the higher levels:

[1] *Annales de l'Observatoire d'Astronomie Physique de Paris* (Meudon), **4**, 103, 1910.

[2] *Publications of the Yerkes Observatory*, **3**, Part I, p. 16.

[3] *Comptes Rendus*, **138**, 1377, 1904.

En général, sur les parties brillantes, les déplacements sont vers le rouge; et la vapeur descend dans l'atmosphère. Comme alors elle se comprime et s'échauffe, l'augumentation de son éclat est naturelle.[1]

A somewhat analogous explanation of the bright reversals over the general disk was suggested by the writer,[2] namely, an increase of radiative power produced by the mutual interaction of the rising emitting vapor and the descending absorbing vapor, their relative velocity being found to be about 3 km per second. A small rise of temperature would probably be sufficient to account for the increased radiation, as Mr. King's work with the furnace has shown that the H and K lines are high-temperature lines in the sense that, with rise in temperature, they increase markedly in intensity in comparison with the arc lines, and without decided widening.[3] The temperatures available in Mr. King's experiments with the electric furnace did not exceed 3000° C. At solar temperatures the same increment of temperature would be less effective in increasing radiation, but that this characteristic of the H and K lines still obtains at solar temperatures is indicated by their great intensity in the sun as compared with that of λ 4226.9, which at low furnace temperatures is stronger than H and K. This explanation would have less force over the faculae where the calcium vapor has little if any upward velocity, while over these regions the radiation of the calcium vapor is the most intense.

A very different cause is assigned for the origin of the bright lines H_2 and K_2 by Professor Julius in his "Spectroheliographic Results Explained by Anomalous Dispersion."[4] This demands a density-gradient at right angles to the line of sight, which he finds in the cross-section of solar vortices:

For it [the density] is a minimum in the axes of vortices; and the average direction of the whirl-cores, lying between the Earth and the central parts of the Sun in the surfaces of discontinuity, differs but little from our line of sight. The rays of the Sun thus reach us after having traveled a great distance along

[1] *Annales de l'Observatoire d'Astronomie Physique de Paris* (Meudon), **4**, p. 77.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 37–39; *Astrophysical Journal*, **32**, 72–74, 1910.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 32, 1908; *Astrophysical Journal*, **28**, 389, 1908.

[4] *Astrophysical Journal*, **21**, 278, 1905.

lines making small angles with the levels of slowest density variation in a lamellar, partly tubular, structure.

Accordingly, the bright lines H_2 and K_2 come from photospheric light of wave-length very near to that of the central absorption line, whose divergence has been changed to convergence by the tubular structure and thus reaches the earth with increased intensity. A serious difficulty involved in this explanation is that it demands that the axis of the tubular structure be always directed toward the earth. If the direction of the whirl-cores differs but little from our line of sight when they occur in the central portions of the sun, the direction must be nearly at right angles to our line of sight when they rise from the peripheral regions since they are approximately normal to the solar surface; but the spectroheliograph shows the flocculi near the sun's limb reduced in width as they would be by foreshortening if they were really bright surfaces. It is very easy to convince oneself by the examination of a series of daily spectroheliograms that the flocculi appear as bright surfaces attached to the sun would appear in projection when carried across the line of sight by the sun's rotation.

It is evident that the bright reversal of the K line over the general disk and the increased intensity of the emission line K_2 over the facular region in comparison with the intensity over the general surface have not yet received a generally accepted explanation. An explanation of these reversals is here based upon the different radiation coefficients for the different parts of the line, and the molecular scattering of light. For the lower layer there is general agreement among solar spectroscopists, namely, that the density of this layer is the basis for the great width of the line, and that for the central portion of the line, at least, the absorption is complete. The temperature of this layer being less than the source of the continuous spectrum background, a broad line darker than the continuous spectrum is produced. In the case of the next layer, the so-called emitting layer, its pressure and temperature are both reduced in reference to the underlying layer. The decrease of pressure results in a narrower line, but its lower temperature does not necessarily imply a decreased radiation, as on nearing the center of the line the coefficient of radiation rapidly increases, and if the

gain due to a higher coefficient of radiation exceeds the loss due to decrease of temperature the result would be a relatively narrow bright line superposed upon the center of the K_1 line. This result would be favored by the greater scattering of the light coming from the lowest layer, which would tend to darken the background by reducing the light in the K_1 line.

Spectroheliograms taken with the first slit on the K_1 line, at decreasing distances from the center of the line, and then with the slit on the K_2 line, in the opinion of solar observers, represent different levels in the solar atmosphere, rising in level as the slit approaches the center of the line. The area of a flocculus increases progressively, reaching its maximum area, according to M. Deslandres, when photographed by the light from the K_3 line. These appearances have been interpreted as indicating a tree-like structure of the rising column of calcium vapor. A diagram illustrating this view is given by W. J. S. Lockyer in *Nature*, **69**, 611, 1904. This implies that the calcium vapor is rising over the faculae, an assumption which the wave-length measurements obtained in this investigation do not appear to justify.

An explanation of the effects obtained at different levels by employing the parts of the K line in taking monochromatic photographs is here based upon the selective absorption in different parts of the K line which determines the depths in the solar atmosphere from which light of the different parts of the line reaches us, and upon the great sensitiveness of the H and K lines to changes of temperature or excitation. The faculae may be considered as regions from which a disturbance is propagated into the overlying gaseous masses. These may be regions of higher surface-temperature, absolutely or from their being elevated above a portion of the surrounding vapors, or as Professor Newall suggests:

> Under the influence of local disturbances, regions of the Sun may emit corpuscles which succeed in penetrating the lower strata of the reversing layer, and cause higher strata to glow as if their effective temperature were higher than lower strata, and thus bright flocculi arise.[1]

In either of the above cases the disturbing influence would tend to spread radially from the center of disturbance and increase

[1] *Monthly Notices of the Royal Astronomical Society*, **69**, 343, 1909.

the radiation coefficient of the calcium vapor perhaps selectively even within the K line. Mr. King has shown in his work with the electric furnace that the intensity of the H and K lines is very susceptible to temperature changes without corresponding changes in the width. For a narrow range of wave-length, represented by the width of K_3, the radiation increment may be assumed to be large; through a range of wave-length corresponding to the difference between the widths of K_3 and K_2 the increment would

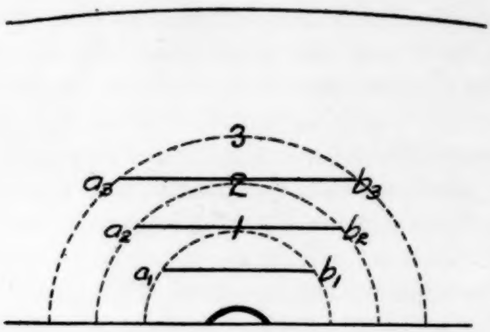


FIG. 3

be less; while for wave-lengths between the boundaries of K_2 and K_1 the increment would be extremely small. The diagram in Fig. 3 will illustrate the manner in which the area of a flocculus would vary for different parts of the H and K lines.

The distance of the line a_3 b_3 below the upper surface indicates the depth to which we see into the solar atmosphere by the light of the K_3 line; the half-circle marked 3 represents the limit of the appreciable effect upon the K_3 line produced by the disturbance propagated from the facula. As the first slit of the spectroheliograph, set upon the K_3 line, moves over the region an area much larger than the facula would be bright relatively to that photographed by the neighboring parts of the K_3 line. For wave-lengths differing slightly from K_3 the increase of radiation would not be so great for equal excitation, but the depth from which the light comes would be greater. The level therefore from which the light of the K_2 line comes, is lower owing to the decreased absorp-

tion. At this depth the excitation may be intense enough to be effective upon the radiation of this wave-length, thus increasing the intensity of K_2 in comparison with the intensity of the adjoining parts of the line. The area photographed by the K_2 line would be less than that photographed by the K_3 line, but still considerably larger than the facula as indicated in the diagram by the line a_2 b_2 and the corresponding circle.

In the case of the K_1 line the light comes from a still greater depth, but for wave-lengths differing so much from the center of the line the increased excitation is very much less effective in increasing radiation than in the case of K_2 and K_3, and the distances from the center of disturbance at which the excitation is sufficient to increase the radiation in K_1 over the facula in comparison to the radiation in the neighboring parts of the line are much less, and the areas photographed by setting the first slit of the spectroheliograph at increasing distances from K_3 would approach the area of the facula as a limit.

There is probably a piling up of calcium vapor over the penumbrae of spots and the surrounding faculae, evidenced both by the greatly increased width of the K_2 line over these regions and the absence of appreciable motion of ascent or descent of the emitting vapor as shown by the wave-length determinations, though it is rising rapidly over the general surface. It is difficult to believe that it is not rising through the faculae as elsewhere. The descent of the upper portions of the layer toward the umbrae of spots and the great thickness of the layer would tend to mask the rising vapor that is probably being added to the mass from below and perhaps crowding it slowly upward, the down-flow into the umbrae being supplied by the inflow from the surroundings of the flocculi. That there is an intimate connection between the faculae and the accompanying flocculi is indicated by their community of form and location. Such a nodal condition as is indicated by the normal wave-length of the K_2 line over the faculae surrounding spots might be favorable to an accumulation of calcium vapor as a kind of back-water effect where opposing currents tend to annul each other. The observations upon which this paper is founded were made upon completely developed spots. It would probably give

added light to the subject to study the motions of calcium vapor over developing faculae and spots, and be particularly interesting to observe the initial conditions in the case of a large flocculus.

From the point of view of the combined action of absorption and scattering, Professor Schuster[1] has considered the radiation of a gaseous layer of uniform temperature and of a layer in which the temperature variation is such that the radiation of a black body varies directly with the distance from the front surface. In the latter case, the only one which approximates solar conditions, he shows that for certain values of the coefficients of absorption and scattering homogeneous radiations may appear bright with a dark center. Bright in this sense means brighter than the continuous spectrum, but the solar H_2 and K_2 lines are less bright than the continuous spectrum. Professor Schuster finds that for certain values of the coefficients the intensity of homogeneous radiations rises to a maximum which is greater than the intensity of the continuous spectrum, then falls for larger values of the coefficient of absorption which obtain as the center of the line is approached. The problem to be solved, however, is that in which the intensity-curve for the line has a minimum corresponding to K_1, a maximum corresponding to K_2, and a second minimum corresponding to K_3, all less than the continuous spectrum, and occurring with progressively increasing coefficients of absorption and progressively decreasing thicknesses of the effective layers. Its solution requires a knowledge of the coefficient of scattering, and of the radiation-gradient which probably differs greatly for the wave-lengths concerned in the production of the K_1, K_2, and K_3 lines; as Professor Schuster points out, the radiation-gradient depends not only on the temperature-gradient but also on the wave-length.

GENERAL CONCLUSIONS

1. In the great majority of sun-spots the calcium vapor is descending in the umbrae with velocities varying from 0.68 km per second to 2.2 km per second. This result is obtained from the usual bright reversal over the umbrae and also from the absorption

[1] *Astrophysical Journal*, **21**, 1, 1905.

line when present. Occasionally the calcium vapor is rising in the umbrae.

2. Over the penumbrae of spots the calcium vapor which is the source of the bright line K_2 has little, if any, vertical motion. The calcium vapor producing the absorption line is descending with approximately the same mean velocity as over the general disk.

3. Over flocculi surrounding spots the emitting vapor shows a very slight but doubtful upward motion. The mean wave-length for K_2 over the central flocculi is 3933.665 Å compared with 3933.667 Å in the arc, an agreement within the errors of measurement. The absorbing vapor, the source of the K_3 line, is descending with the same mean velocity as over the general disk.

4. Over circumfloccular regions the upper layer of absorbing calcium vapor is descending with practically the same mean velocity as over the general disk, and does not show evidence of a local system of circulation involving the flocculi and their immediate surroundings.

5. A radial motion of the calcium vapor inward across the penumbrae is shown both by the emitting and absorbing vapor. The velocity is higher for the absorbing vapor than for the emitting vapor.

6. A rotary motion of the calcium vapor around the umbrae of spots is an occasional phenomenon, and is shown by the displacements of both the absorption line and the bright line. The velocity is higher in the case of the absorbing vapor than in the case of the emitting vapor.

7. The combination of the radial motion inward and the rotary motion results in a spiral or a vortical motion converging upon the umbra. The direction of rotation does not depend upon whether the spot is north or south of the sun's equator. The disturbance appears to originate in the high-level absorbing vapor and to work downward, involving the emitting layer.

8. The phenomenon of a dark absorption line appearing in one of the K_2 components, or beyond their outer edges, while the K_3 line is undisturbed, is interpreted as being caused by detached masses of relatively cool calcium vapor high above the chromo-

sphere, and in more or less rapid motion, that is, by prominences projected against the sun's disk.

9. In addition to the general circulation of the calcium vapor shown by the ascent of the emitting vapor and the descent of the absorping vapor over the general surface of the sun, there appears to be a local system in which the emitting vapor rises around the flocculi, flows across the penumbra, and is then drawn downward into the umbra with or without vortical motion. There is very slight evidence, if any, of its rising from the interior of the sun through the faculae, except in the case of eruptions.

10. The intensity of the bright K_2 line over flocculi is less than that of the continuous spectrum. The apparent weakness of the K_2 line in the spectrum of the center of the sun is due mainly to the slight difference between it and the background of the K_1 line. Its apparent increase of intensity at the limb is due in the main to the greater absorption in the K_1 and K_3 lines which raises the K_2 line into relief without much actual increase of intensity.

11. The relative intensities of the K_1, K_2, and K_3 lines may be explained by the great differences in their radiation coefficients and the consequent different depths in the solar atmosphere from which light of their respective wave-lengths reaches the surface owing to selective absorption. The occurrence of the bright emission line K_2 would be favored by the scattering of the light from the still lower layer.

12. The results for different levels obtained by the spectroheliograph find a possible explanation through considering the underlying faculae as sources of disturbance propagated into the overlying masses of calcium vapor and increasing in different degrees the radiation coefficients of the components of the K line.

Mount Wilson Solar Observatory
March 1911

AN INCLOSED ARC FOR SPECTROSCOPIC WORK

By JAMES BARNES

During the past few years the author has been engaged in the study of the spectra of a number of substances in the arc burning in gases under reduced pressure. Different kinds of vessels for holding the arc were constructed, but none gave perfect satisfaction. Often when long exposures were necessary, the heat developed loosened some of the joints so that the pressure could not be kept constant. When certain electrodes, as aluminium, were used, the arc easily went out and could not be started again, due to the fact that the air which entered the vessel united with the hot poles, forming a nonconducting film on their surfaces. Opening the vessel and its readjustment took considerable time, and often the exposed photographic plate was spoiled by the many changes.

In the vessel described in this paper these troubles and many others of less importance have been eliminated. The arc can be kept burning as long as the electrodes remain intact. It is hoped that the apparatus may be of some use along other lines than those indicated below.

DESCRIPTION

Fig. 1 shows a vertical section of the vessel. The rim, *a*, of a thick-walled bell-jar about 25 cm high and 15 cm in diameter is ground to fit an iron plate, *b*. Through the plate run a number of tubes; *c* is connected to an exhaust pump, pressure gauge, and gas reservoirs; d_1 and d_2 are the ends of a lead pipe wound round a sheet-iron cylinder, *e*, and there are two more, *f*, which will be described later. An opening is bored in the jar and a short glass tube, *g*, is sealed into it by means of a preparation called "Caementium." This tube closed by a quartz plate gives a ready exit for the radiations from the arc.

The upper electrode, *h*, is held by a brass tube fixed into the neck of the jar with the above preparation and sealing-wax. This tube contains an inner pipe, *l*. Connecting *k* with *d* by means

of rubber tubing and *l* with a source of running water the whole vessel is kept cool. A thin iron disk is placed at *m* to protect the upper part of the vessel from radiation.

The lower electrode, *j*, is held at the end of the long arm of a lever made of an iron bar pivoted at *n*. This electrode is raised to make the arc by holding in the hand near the short arm of the lever a small electro-magnet. When the magnet is removed the electrode falls back to its original position. The screw, *o*, regulates the distance between the poles. To prevent sparking at the pivot a loose wire, *r*, connects the lever with the base to which is fixed the negative binding post.

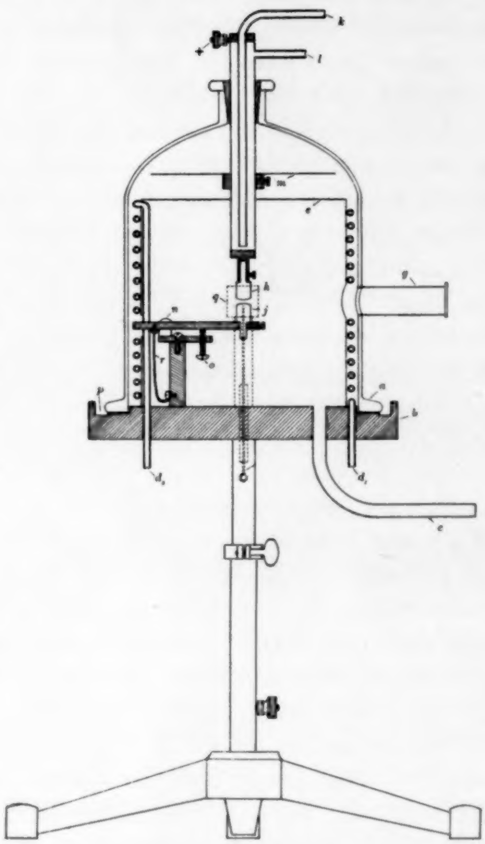


FIG. 1

In order to have no leakage at the ground joint it is necessary to cover the surfaces with a thin layer of grease. A preparation called "Albany grease" was found to be very satisfactory for this purpose. For pressures below a millimeter it is better to cover them with a stopcock lubricant such as that suggested by Travers,[1] and to fill the cavity, *p*, with mercury. By this means and a Gaede pump working continuously, very low pressures can be reached. Care

[1] *Study of Gases*, p. 24.

must be taken to have both the ground surfaces perfectly clean before the application of the grease.

Another way for starting the arc suggested itself during the observations and it led to a few interesting observations. Two small square aluminium plates, *q*, were placed in the vessel in such a position that the poles of the arc rested between them. Wires attached to these plates and sufficiently insulated with ebonite and glass tubes were led through the iron base at *f* and then connected with the terminals of a large induction coil. The discharge from this coil passing through the gap between the poles at once starts the arc when the pressure is sufficiently low. This is true for all the substances so far tried, viz., aluminium, magnesium, calcium, copper, carbon, and iron; in the case of the last three substances it is interesting to note that this method of relighting the arc is successful only when the poles have cooled down so that they do not glow. There is no delay in remaking the arc with the other three substances as electrodes. The current used for the arc was direct, from a 220-volt circuit.

OBSERVATIONS

The arc under reduced pressure gives spectra which are not only purer than those obtained from the arc in air, but the lines are narrower and sharper. This is of much importance for exact measurement of wave-lengths. The narrowness of the lines is best shown by the interference bands they produce when passed through an interferometer. A Fabry and Perot instrument, of the type discussed in a former[1] note, was used and the interference pattern focused on the slit of a Hilger constant-deviation spectroscope. It was found that the bright lines of the iron, copper, and brass arcs *in vacuo* give interference fringes which are much more distinct than those obtained from the same arcs in air. In the case of substances like cadmium it is almost impossible to obtain any interference pattern in any of the lines, but when an iron electrode is bored out and filled with the metal, and then used for one electrode in the arc under reduced pressure, the pattern appears very clearly. The interference fringes are just as sharp as those

[1] *Nature*, **80**, 187, 1909.

obtained by using an Heraeus cadmium quartz lamp. This cadmium arc runs very steadily, and with proper adjustment of the current-strength will run for hours on one filling. Through the kindness of Dr. Pfund, I was able to observe the interference pattern produced by the radiations of iron, and iron filled with barium carbonate in the arc *in vacuo* after passing through his[1] apparatus employed for the determination of standard wave-lengths. The

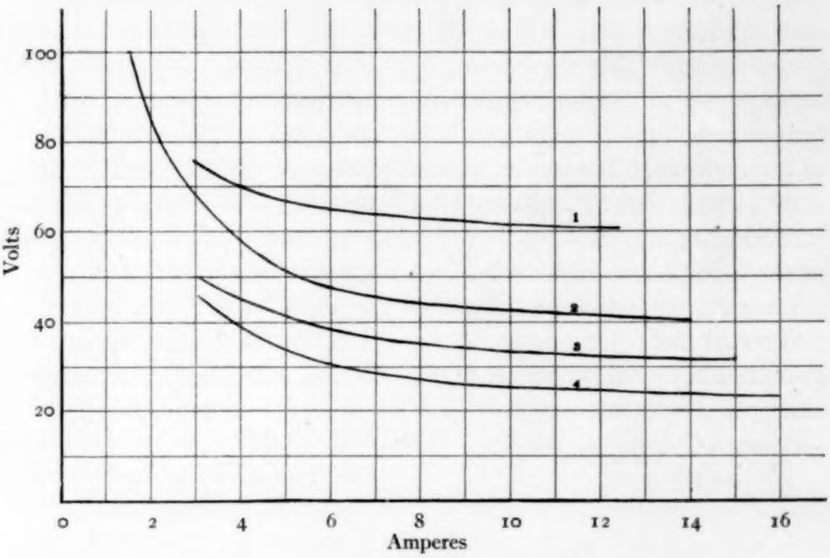


FIG. 2.—1. Carbon arc, atmospheric pressure. 2. Carbon arc, 1 cm pressure. 3. Magnesium arc, atmospheric pressure. 4. Magnesium arc, 1 cm pressure.

observations corroborated those obtained with the less elaborate apparatus; the sharpness of the red and green lines of barium was very marked. I wish to express my thanks to Dr. Pfund for the privilege of using his apparatus and for his assistance in making the observations.

This method of obtaining a large number of very bright monochromatic lines by using a number of substances for electrodes should be of use in experiments for the determination of indices of refraction by interference methods.

[1] *Astrophysical Journal*, **28**, 197, 1908.

A series of observations on the fall of potential across the arc with varying current-strengths was made. Fig. 2, curves 1 and 2, shows the average results of these observations upon the carbon arc in air at atmospheric pressure and at a pressure of 1 cm, respectively. Curves 3 and 4 are those for magnesium. It will be noticed that the voltage across the arc in air is always larger than that across the arc *in vacuo* for the same current-strength and material. The slopes of 1 and 3 are approximately the same, and of 2 and 4 are the same; the rate of change of voltage with current is, however, greater for the arcs *in vacuo* than for the arcs in air, so that for 12 amperes there is a difference of almost 20 volts between the two arcs in the case of carbon and 10 volts in the case of magnesium. These differences are large compared with the total fall of potential. Many times the arc has been seen to leave one terminal and end about 10 cm away on some part of the apparatus. It appears to be a centimeter or more in thickness and is somewhat like a vacuum-tube discharge in a large tube when the pressure is between 1 and 0.5 cm. In this arc the difference of potential between the terminals is over 125 volts and the current-strengths between 1 and 2 amperes.

Bryn Mawr College
April 1911

THE SPECTRA OF ALUMINIUM, COPPER, AND MAGNESIUM IN THE ARC UNDER REDUCED PRESSURE

By JAMES BARNES

The study of the spectra of the elements in the arc and spark under various conditions has been the subject for a very large amount of investigation. The effects produced by reducing the pressure of the gas surrounding the arc has not been thoroughly investigated except in the case of magnesium[1] and calcium,[2] where it was found that at pressures of a few millimeters of mercury the relative intensities of many lines are quite different from their relative intensities in the arc in air at atmospheric pressure. Some lines and bands disappear completely, others make their appearance. An interesting illustration of this is the important line λ 4481 of magnesium. This line is one of the strongest in the spectrum of the arc *in vacuo*, while it is one of the weakest in the arc in air when the current is greater than 3 amperes. Similarly with the calcium bands with heads at λ 6382 and λ 6389, they appear with considerable intensity in the arc *in vacuo*. These flutings are an important feature of sun-spot spectra.

The present paper contains the results of an investigation on the spectra of aluminium and copper in this arc, together with a few further observations on the magnesium spectrum.

APPARATUS AND MEASUREMENTS

The spectra were observed and photographed in the first order of a Rowland concave grating of six feet radius. The dispersion was about 9.33 Å to the millimeter. The apparatus for obtaining the arc under reduced pressures was much improved over that used in earlier work and has been described in the preceding article.[3] Both electrodes were made from rods of the metal and were about 1 cm in diameter. The current used was direct, and was taken

[1] Fowler and Payn, *Proc. R.S.*, **72**, 254, 1903; J. Barnes, *Astrophysical Journal*, **21**, 74, 1905; E. E. Brooks, *Proc. R.S.*, **80**, 218, 1908.

[2] J. Barnes, *Astrophysical Journal*, **27**, 152, 1908, and **30**, 14, 1909.

[3] *Astrophysical Journal*, **33**, 154, 1911.

from a 220-volt circuit. Its strength depended upon the material of the electrodes used.

The wave-lengths of the lines of the aluminium band, which have been measured as accurately as possible, are expressed in terms of the new standards. The wave-lengths of the iron lines employed were taken from Kayser's recent work,[1] "Standards of Third Order of Wave-Lengths on the International System." The measurements were made in the usual way from plates containing the metal and iron spectra by means of a Gaertner micrometer-microscope graduated to 0.001 mm. These plates were taken by exposing one-half of the slit to the metal arc and the other half to the iron arc. Since the plate-holder was not touched during the entire exposure, any displacement of the spectra relative to one another was eliminated. A number of settings was always made on a line and the mean taken. At least two plates were used.

For comparing easily and quickly the spectrum *in vacuo* with that in air, plates were taken by moving the holder so that one spectrum was above the other. This produced a slight shift in one direction or the other. The reproductions on Plate IX were taken in this way.

ALUMINIUM

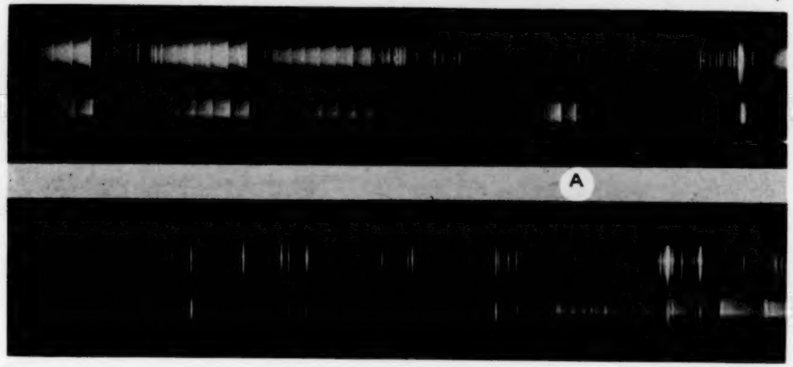
There is an unmistakable difference in the relative intensities of many of the lines in the arc *in vacuo* compared with their intensities in the arc in air, all other conditions, especially the current-strength, being kept constant. This was about 3 amperes; larger currents caused the electrodes to flow. When the pressure of the air surrounding the arc was about 0.5 cm, the so-called spark lines[2] made their appearance, some with quite considerable intensities, such as $\lambda\lambda$ 4663, 3587, and 2631. Many of these lines in the spark are weakened when self-induction is added to the circuit.[3] The line λ 2816 is worthy of special mention on account of its increase in the vacuum arc. It has also other properties in common

[1] *Astrophysical Journal*, **32**, 217, 1910.

[2] Steinhausen, *Zeitschrift für wissenschaftliche Photographie*, **3**, 45, 1905.

[3] A. S. King, *Astrophysical Journal*, **19**, 237, 1904.

PLATE IX



SPECTRA UNDER REDUCED PRESSURE

with λ 4481 of magnesium, such as the change of intensity with current-strength.

Within recent years much interest has centered about the four groups of bands lying between λ 5211 and λ 4471. Lockyer suggested that these radiations were due to a compound of aluminium and oxygen. Berndt[1] came to the same conclusion. Arons,[2] Hemsalech,[3] and Hartley[4] believe that they are not due to the oxide but to the metal itself. My observations show that these bands occur just as intense in the arc in air at a pressure of a millimeter or two as they do in air at atmospheric pressure, so that I am inclined toward the latter view. Basquin,[5] working with a rotating arc in hydrogen, observed for the first time a beautiful fluting with four heads at $\lambda\lambda$ 4241, 4260, 4288, and 4353. These bands, which do not appear in air, come out very strongly in the arc *in vacuo*, as is shown at *A* on Plate IX, Fig. 1. The following table gives their wave-lengths. The iron lines used as standards were $\lambda\lambda$ 4260.484, 4254.334, 4299.243.

*4241.21	4255.20	4267.20	4298.03	4360.46
4241.71	4257.38	4268.80	4302.06	4361.10
4242.26	*4259.68	4270.64	4306.24	4362.07
4243.08	4260.10	4272.69	4310.72	4363.37
4244.09	4260.45	4274.95	4315.46	4365.03
4245.25	4261.08	4277.64	4320.51	4367.08
4246.58	4261.76	4280.65	*4353.27	4369.54
4248.05	4262.55	4283.88	4354.05	4371.36
4249.65	4263.52	4287.17	4355.07	4374.95
4251.36	4264.58	4290.62	4356.45	4378.95
4253.24	4265.80	4294.23	4358.34	

* Indicates heads.

COPPER

The copper arc *in vacuo* is almost as brilliant as it is in air. With the current used, about 8 amperes, both poles became red hot and remained so throughout the exposures. This current-

[1] *Annalen der Physik*, **4**, 788, 1901.

[2] *Ibid.*, **1**, 700, 1900.

[3] *Ibid.*, **2**, 331, 1900.

[4] *Trans. Roy. Dublin Soc.*, **9**, 85, 1908.

[5] *Astrophysical Journal*, **14**, 8, 1901.

strength was found necessary; when more resistance was turned into the circuit the arc quickly went out.

Copper has without doubt a larger number of lines affected by the reduction of pressure than any of the elements so far tried. The change in the intensities of the lines in the region between λ 4870 and λ 3960 are shown on Plate IX, Fig. 2. Different from aluminium and calcium, only the faintest outlines of bands besides those of nitrogen appear on the plates of longest exposure in the places where they have been found by Basquin (*loc. cit.*) in the arc in hydrogen, and by King[1] in the electric furnace. The time of exposure for these plates was about 30 minutes and a wide slit (0.2 mm) was used. These bands are so faint that the author is not sure they are the ones found by the above observers. On the plates taken with 1 and 2 minutes' exposure, which is quite sufficient for good photographs of the line spectra, not a trace of the bands could be seen. The following lines show clearly a decrease of intensity in the arc *in vacuo*. Those with an asterisk are weakened the greater amount.

4866.4	4507.6
4794.2	*4378.4
4767.7	4259.6
*4697.6	*4177.9
*4675.0	*2392.7
4642.8	2293.9
*4587.2	*2263.2
*4540.0	

It will be found on reference to Kayser's *Handbuch der Spectroscopie*, **5**, pp. 401 f., that all of these lines are found in the arc in air, many of them broad and hazy; a few are found in the spark, but always with a smaller intensity than in the arc. Mention should be made of $\lambda\lambda$ 4675, 4587, 4378, and 4177, for they are just visible on the plates of longest exposure, while they are among the strongest in the arc in air.

MAGNESIUM

The current used was about 4 amperes. The effect of the reduction of pressure upon the intensities of the arc lines lying between λ 4703 and λ 4058 and upon the spark line λ 4481 have

[1] *Astrophysical Journal*, **21**, 250, 1905.

been recorded (*loc. cit.*). The author wishes to extend these observations to include the following lines, whose relative intensities are considerably increased in the vacuum arc, viz.: $\lambda\lambda$ 2790.9 2798.1, 2928.9, 2936.8, and 3107.1; the first four are intense spark lines. The two pairs at $\lambda\lambda$ 4433.6, 4428.2, 4390, and 4385, which Brooks calls the "F and P" lines, also appear strongly.

The so-called oxide and hydride bands appear on the plates of the spectrum of the arc in air at a few millimeters pressure.

CONCLUSIONS

The results of the observations upon the spectra of the elements which have been investigated so far in the arc under reduced pressure may be divided into two classes.

1. The bands which have been attributed to compounds of oxygen and hydrogen with aluminium, magnesium, and calcium all appear very clearly in this arc. Whether or not they are true oxide or hydride bands one must admit is still an open question. For it can always be claimed that there is enough oxygen left in the vessel surrounding the arc or sufficient hydrogen occluded in the metals to produce these bands. It might be of interest to state in this connection that the hydrogen lines could not be found on the plates, while the nitrogen bands were very clear.

2. With regard to the lines, the effect of the reduction of the pressure is in general to increase the intensity of the spark lines of aluminium and magnesium, and to diminish many of the arc lines of copper. Whatever the explanation of this may be, one can state that the arc *in vacuo* is a step between the arc in air and the spark, although the potential-drop between the electrodes in this arc is always smaller than that in air for the same current-strength. The lines mentioned in this paper, which are those whose intensities change the most, do not belong to the Principal or Subordinate Series in Kayser's arrangement.

In conclusion I wish to express my thanks to two of my students, Miss Frehafer and Miss Howson, for assistance in making these observations.

BRYN MAWR COLLEGE
April 1911

AN INQUIRY INTO THE VARIATION OF THE SPECTROSCOPIC BINARY *κ PAVONIS*

By ALEX. W. ROBERTS

When the binary character of *κ Pavonis* was certified to by Wright,[1] its variation became matter of very careful inquiry. In order to obtain measures of this star—and also of *l Carinae* and *v Puppis*, both bright spectroscopic binaries—as free from systematic error as possible, a mode of observation was adopted that, I think, has proved satisfactory.

Briefly stated, the variable and its comparison stars are observed in a plane mirror, so mounted that the field can be rotated through any angle. Four observations, one in each quadrant, are taken by eye estimates. These determinations are then reduced for scale-value and standard value. One observation is considered to be the mean of the four determinations.

In order to free the mind from any bias, no ephemeris of the star was constructed and frequently observations were dropped for some weeks in order to eliminate any conception regarding its variation that might unconsciously have arisen during the progress of the observations. The star's period seems subject to secular change, and since this variation has not been sufficiently determined, I shall confine myself, in the present paper, to a discussion of the 1910 observations. These exhibit the chief features of variation that it is the purpose of this paper to consider.

The following table sets forth these observations. In column 1 is given the date of observation; in column 2, the Julian date of observation; in column 3, the date of observation reduced to mean curve, taking as mean period

$$9.09106 \text{ days;}$$

in column 4 is found the observed magnitude; column 5 gives the magnitudes computed from the mean curve for the year 1910, and column 6 gives the (O.—C.) residuals.

[1] *Lick Observatory Bulletin*, **3**, 3, 1904; *Astrophysical Journal*, **20**, 141, 1904.

1910 OBSERVATIONS OF κ *PAVONIS*

Date	Julian Day	Reduced Date	Obs. Mag.	Comp. Mag.	O.−C.
	24187				
April 2^{d} $9^{h}52^{m}$	64.41	2419028.05	$3^{m}69$	$3^{m}86$	$-0^{m}17$
3 11 25	65.48	029.12	3.85	3.71	+0.14
11 50	65.49	029.13	3.85	3.71	+0.14
12 30	65.52	029.16	3.86	3.72	+0.14
4 9 10	66.38	030.02	4.24	4.21	+0.03
7 9 45	69.41	023.96	5.28	5.21	+0.07
10 9 10	72.38	026.93	4.84	4.90	−0.06
10 40	72.44	026.99	4.84	4.89	−0.05
11 50	72.49	027.04	4.73	4.87	−0.14
11 8 25	73.35	027.90	4.08	3.98	+0.10
10 25	73.43	027.98	3.97	3.92	+0.05
15 10 55	77.46	022.92	4.92	4.98	−0.06
30 7 56	92.33	028.69	3.87	3.67	+0.21
May 3 8 10	95.34	022.61	4.85	4.90	−0.05
9 5	95.38	022.65	4.82	4.91	−0.09
10 3	95.42	022.69	4.87	4.91	−0.04
11 40	95.49	022.76	4.97	4.94	+0.03
4 9 25	96.40	023.67	5.11	5.15	−0.04
6 8 55	98.37	025.64	5.08	5.13	−0.05
10 0	98.42	025.69	5.06	5.12	−0.06
7 8 50	99.37	026.64	5.03	4.98	+0.05
9 10	99.38	026.65	4.97	4.98	−0.01
14 55	99.62	026.89	4.93	4.91	+0.02
15 25	99.64	026.91	4.91	4.91	0.00
	24188				
8 9 15	00.39	027.66	4.28	4.19	+0.09
10 15	00.43	027.70	4.23	4.15	+0.08
11 5	00.46	027.73	4.24	4.13	+0.11
9 7 35	01.32	028.59	3.74	3.67	+0.07
8 30	01.35	028.62	3.82	3.67	+0.15
9 25	01.40	028.67	3.73	3.67	+0.06
10 7 20	02.31	029.58	3.86	3.94	−0.08
8 30	02.35	029.62	3.88	3.92	−0.04
10 0	02.42	029.69	3.98	4.00	−0.02
12 8 50	04.37	022.55	(4.60)	4.89	(−0.29)
9 35	04.40	022.58	4.76	4.89	−0.13
13 6 55	05.29	023.47	5.15	5.11	+0.04
14 7 15	06.30	024.48	5.24	5.24	0.00
8 30	06.35	024.53	5.29	5.24	+0.05
15 9 25	07.39	025.57	5.20	5.16	+0.04
10 10	07.42	025.60	5.10	5.15	−0.05
16 9 56	08.41	026.59	5.05	4.98	+0.07
12 40	08.53	026.71	5.02	4.97	+0.05
June 1 6 30	24.27	024.27	5.20	5.23	−0.03
7 55	24.33	024.33	5.19	5.24	−0.05
9 12	24.38	024.38	5.21	5.24	−0.03
10 15	24.43	024.43	5.20	5.24	−0.04
2 6 43	25.28	025.28	5.26	5.20	+0.06
7 40	25.32	025.32	5.21	5.20	+0.01
9 26	25.39	025.39	5.21	5.19	+0.02
3 6 35	26.27	026.27	5.00	5.01	−0.01
7 50	26.33	026.33	5.01	5.01	0.00
10 30	26.44	2419026.44	5.01	5.00	+0.01

1910 OBSERVATIONS OF κ *PAVONIS*—*Continued*

Date	Julian Day	Reduced Date	Obs. Mag.	Comp. Mag.	O.−C.
	24188				
June $3^d\,15^h\,30^m$	26.65	2419026.65	4^m96	4^m97	-0^m01
4 10 0	27.42	027.42	4.43	4.39	+0.04
5 7 30	28.31	028.31	3.68	3.71	−0.03
8 35	28.36	028.36	3.66	3.69	−0.03
9 30	28.40	028.40	3.69	3.68	+0.01
6 5 45	29.24	029.24	3.66	3.75	−0.09
6 45	29.28	029.28	3.70	3.76	−0.06
8 5	29.34	029.34	3.67	3.79	−0.12
10 0	29.42	029.42	3.72	3.83	−0.11
9 8 10	32.34	023.25	5.07	5.06	+0.01
9 20	32.39	023.30	5.06	5.07	−0.01
9 50	32.41	023.32	5.09	5.08	+0.01
11 6 10	34.26	025.17	5.25	5.21	+0.04
6 58	34.29	025.20	5.21	5.21	0.00
14 5 0	37.21	028.12	3.78	3.81	−0.03
15 5 40	38.24	029.15	3.67	3.71	−0.04
9 3	38.38	029.29	3.67	3.77	−0.10
10 25	38.43	029.34	3.67	3.79	−0.12
19 11 45	42.49	024.31	5.19	5.23	−0.04
15 55	42.66	024.48	5.22	5.24	−0.02
July 25 6 55	78.29	023.75	5.27	5.17	+0.10
26 6 25	79.27	024.73	5.24	5.24	0.00
30 6 55	83.29	028.75	3.63	3.67	−0.04
8 45	83.36	028.82	3.62	3.67	−0.05
9 40	83.40	028.86	3.62	3.68	−0.06
10 30	83.44	028.90	3.66	3.68	−0.02
Aug. 3 5 16	87.22	023.58	5.23	5.14	+0.09
6 0	87.25	023.61	5.15	5.14	+0.01
7 25	87.31	023.67	5.15	5.15	0.00
8 36	87.36	023.72	5.15	5.16	−0.01
9 36	87.40	023.76	5.12	5.17	−0.05
5 5 0	89.21	025.57	5.10	5.16	−0.06
6 30	89.27	025.63	5.07	5.14	−0.07
8 50	89.37	025.73	5.08	5.11	−0.03
9 55	89.42	025.78	5.06	5.09	−0.03
11 5	89.46	025.82	5.05	5.08	−0.03
12 30	89.52	025.88	5.05	5.07	−0.02
6 8 13	90.34	026.70	4.89	4.97	−0.08
9 25	90.39	026.75	4.96	4.96	0.00
10 38	90.44	026.80	4.99	4.95	+0.04
7 5 25	91.22	027.58	4.20	4.24	−0.04
7 35	91.32	027.68	4.06	4.16	−0.10
8 55	91.37	027.73	4.00	4.13	−0.13
15 0	91.63	027.99	3.73	3.90	−0.17
10 5 10	94.22	030.58	4.54	4.54	0.00
6 30	94.27	030.63	4.59	4.57	+0.02
8 43	94.36	030.72	4.65	4.61	+0.04
9 45	94.41	030.77	4.59	4.63	−0.04
11 5 45	95.24	022.51	5.03	4.87	+0.16
7 40	95.32	022.59	4.98	4.90	+0.08
9 40	95.40	022.67	5.00	4.91	+0.09
10 30	95.44	022.71	4.93	4.92	+0.01
11 15	95.47	022.74	4.94	4.93	+0.01
15 15	95.64	2419022.91	4.94	4.97	−0.03

1910 OBSERVATIONS OF κ *PAVONIS—Continued*

Date	Julian Day	Reduced Date	Obs. Mag.	Comp. Mag.	O.−C.
	24189				
Sept. 13^d $7^h 30^m$	28.31	2419028.31	3^m61	3^m71	-0^m10
8 50	28.37	028.37	3.64	3.69	−0.05
22 7 10	37.30	028.21	3.86	3.76	+0.10
9 10	37.38	028.29	3.71	3.71	0.00
Oct. 31 6 35	76.19	030.74	4.79	4.62	+0.17
7 28	76.31	030.86	4.75	4.65	+0.10
Nov. 1 6 25	77.27	031.82	5.02	4.93	+0.09
6 55	77.29	031.84	4.96	4.93	+0.03
8 0	77.33	031.88	5.04	4.95	+0.09
2 7 30	78.31	023.77	5.08	5.18	−0.10
8 6 30	84.27	029.73	4.08	4.03	+0.05
9 6 25	85.27	030.73	4.73	4.61	+0.12
7 50	85.33	2419030.79	4.60	4.64	−0.04

Average error of a single observation = $\pm 0^m057$

Grouping together the dates given above in column 3, we obtain the following mean magnitudes of κ *Pavonis*, using 1910 observations only.

MEAN LIGHT-CURVE: 1910

No. of observations	Date	Mean Mag.	Mag. from Light-Curve	O.−C.
	24190			
4	22.56	4^m84	4^m88	-0^m04
4	22.66	4.89	4.91	−0.02
4	22.73	4.96	4.93	+0.03
4	22.85	4.97	4.96	+0.01
4	23.34	5.09	5.09	0.00
4	23.63	5.16	5.15	+0.01
5	23.79	5.18	5.18	0.00
5	24.34	5.20	5.23	−0.03
4	24.56	5.25	5.24	+0.01
5	25.27	5.23	5.20	+0.03
5	25.60	5.11	5.15	−0.04
5	25.78	5.06	5.09	−0.03
4	26.41	5.02	5.00	+0.02
4	26.66	4.96	4.97	−0.01
4	26.79	4.98	4.95	+0.03
4	26.97	4.83	4.88	−0.05
5	27.61	4.24	4.23	+0.01
5	27.85	4.00	4.03	−0.03
4	28.17	3.76	3.77	−0.01
4	28.34	3.65	3.69	−0.04
4	28.57	3.75	3.67	+0.08
5	28.80	3.68	3.67	+0.01
5	29.16	3.78	3.72	+0.06
4	29.31	3.68	3.77	−0.09
5	29.61	3.90	3.94	−0.04
4	30.49	4.51	4.50	+0.01
5	30.78	4.69	4.64	+0.05

The light-curve obtained from the data given in columns 2 and 3 is represented in Fig. 1, and the magnitudes indicated by this mean curve find a place in the foregoing tables as the theoretical computed magnitudes. The striking peculiarity of the light-curve of *κ Pavonis* is what appears to be a secondary phase, nearly midway between principal minimum and principal maximum. This secondary phase is very persistent in all the observations of *κ Pavonis*. In those taken during 1907 it is very marked. If, now,

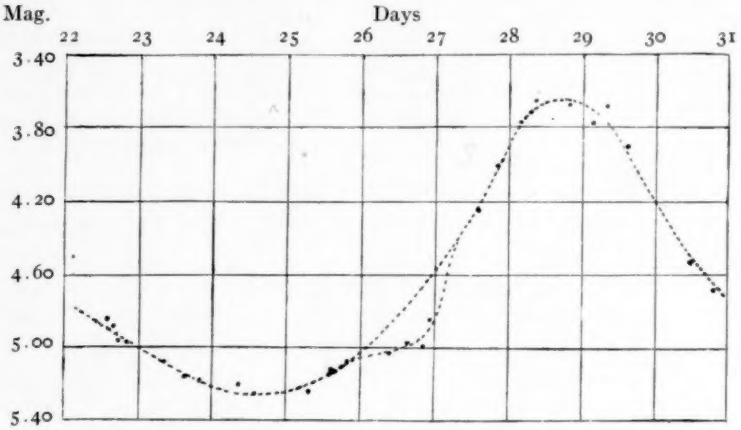


FIG. 1.—Light-curve of *κ Pavonis*, 1910. Julian Day 2419000+

we regard *κ Pavonis* as varying uniformly after the simple type of most short-period variables, we may readily compute the amount of departure of this secondary depression from the fundamental curve. That is, we may regard this simple fundamental curve as the real basis of the star's variation, and the secondary aberration as due to causes of a different order. This fundamental curve, shown as a continuous curve in Fig. 1, may be defined as:

$$\begin{aligned} 4^{m}.62+0^{m}.74 &\cos(\theta-\ 53^\circ\ 45') \\ +0.18 &\cos(2\theta-265^\circ\ 35') \\ +0.07 &\cos(3\theta-142^\circ\ 38') \\ +0.03 &\cos(4\theta-\ 85^\circ\ \ 0') \\ +0.01 &\cos(5\theta-141^\circ\ \ 0'), \end{aligned}$$

where θ is the time after 2419023 expressed in angular measure. The secondary departure from this primary curve becomes:

$2419025^{d}.78$	$-0^{m}.02$
26.41	+0.14
26.66	+0.18
26.79	+0.28
26.97	+0.21
27.59	0.00.

Representing this in the form of a curve, we have the secondary minimum indicated in Fig. 2. Now a curve of this form suggests eclipse. It is indeed a valid and reasonable explanation. Spectroscopic inquiry has proved the duplicity of *κ Pavonis*. It would seem, therefore, that superimposed upon the variation of short-period character, there is, for a portion of the star's period, a diminution in brightness due to the partial eclipse of the secondary star by its primary.

The 1910 observations indicate the following elements of eclipse:

Amplitude of eclipse	$0^{m}.24$
Duration of eclipse	2.0 days
Minimum—central eclipse	2.1 days
Central eclipse—maximum	1.9 days

Taking $2419026^{d}.8$ as the date of central eclipse, that is, the instant when the stars are in the line of sight, and the velocity of approach zero, maximum approach should occur at,

$$2419029^{d}.1$$

and maximum recession at,

$$2419024^{d}.5$$

It will be of no ordinary interest to discover if spectroscopic research confirm these deductions.

Assuming these conclusions to be justified, then in 1910 maximum brightness of *κ Pavonis* took place 0.3 day before maximum approach and minimum brightness 0.2 day after maximum recession.

In the opening portion of this paper, I implied that an unascertained secular change in the period of *κ Pavonis* prevented me from combining all the observations made at Lovedale—considerably over a thousand—into one mean curve. But it may be of interest to state what the 1907 observations reveal regarding the secondary

minimum of *κ Pavonis*. Considering this minimum as due to eclipse, then the following facts emerge:

Amplitude of eclipse	$0^{m}.26$
Duration of eclipse	2.1 days
Minimum—central eclipse	2.1 days
Central eclipse—maximum	2.0 days
Maximum approach	$2417928^{d}.6$
Maximum brightness	2417928.3
Difference	0.3 day
Maximum recession	2417924.0
Minimum brightness	2417924.2
Difference	0.2 day

The curious will notice that the relation of maximum and minimum phases to quadrature passage is exactly the same for 1910 as for 1907, and the relation is in accordance with that rigorously established in the case of other short-period stars.

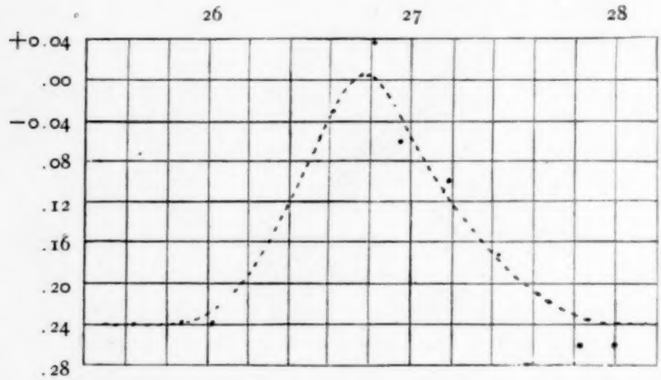


FIG. 2.—Secondary phase of *κ Pavonis*, 1910. Julian Day 2419000+

There is a temptation to compute the relations of size, brightness, inclination, and indirectly density, that would give a light-curve such as is set forth in Fig. 2. But the quantities are quite indeterminate. All we can assure ourselves of is that if eclipse be an explanation of the secondary phase of *κ Pavonis*, then the central star is larger, darker, and more massive than its satellite. Also we may conclude that the rotation and revolution of both stars are

not synchronous. More than this, at this present stage, we are unable to say.

A rigorous investigation of the orbital movement of this star is urged upon those who have the necessary equipment for such an inquiry. For if it can be placed beyond the region of doubt that the binary character of *κ Pavonis* is as we have here urged, then we have moved forward somewhat toward a fuller understanding of the nature and cause of short-period variation.

LOVEDALE, SOUTH AFRICA
December 1910

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